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SRI International, Menlo Park, Calif

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Assessment of Human Exposures to Atmospheric Benzene

by

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PREFACE

There is substantial evidence that concentrations of benzene encountered in the workplace (both in the United States and elsewhere) have caused blood and bone marrow diseases (e.g., blood dyscrasia, pancytopenia) and leukemia (especially myelogenous leukemia). As current U.S. Environmental Protection Agency (EPA) policy states that there is no zero risk level for carcinogens, benzene has been listed by EPA under Section 112 of the Clean Air Act as a hazardous air pollutant. To determine what regulatory action should be taken by EPA on atmospheric emissions of benzene, three reports have been prepared: (1) a health effects assessment, (2) a population exposure assessment, and (3) a risk assessment document based on the data in the first two assessments. This document is the human population exposure assessment and presents estimates of the numbers of people in the general population of the United States exposed to atmospheric concentrations of benzene from specific sources.

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I SUMMARY

This report is one in a series that SRI International is providing on a quick-response basis for the U.S. Environmental Protection Agency (EPA). Populations-at-risk to selected pollutants are being quantified for input to other, more inclusive studies. The primary objective of this study was to estimate the environmental exposure of the U.S. population to atmospheric benzene emissions from specific sources. In this estimate it was assumed that individuals residing in the vicinity of benzene sources spend 24 hours of each day in the same location. To estimate more representative exposures, a second objective was added--to make rough estimates of individuals' total exposures by defining "total exposure" as the sum of exposures to all benzene sources, including those in nonresidential areas, within a designated period.

The seven primary sources of atmospheric benzene considered in this report are chemical manufacturing facilities, coke ovens, petroleum refineries, solvent operations, gasoline storage and distribution centers, self-service gasoline stations, and urban exposures related to automobile emissions and evaporation from gasoline service stations.

Data were quite limited for this study. When data were available, source locations were identified and benzene emission rates were calculated. Atmospheric environmental concentrations of benzene were then estimated by applying approximate, dispersion modeling results developed by EPA. Population exposed to concentrations of 0.1 ppb[*] and greater were estimated. When data were unavailable, best estimates were developed to provide a reasonable basis for comparison.

Total exposures were estimated by developing scenarios that represent the typical behavior of individuals living in the vicinity of benzene sources. Based on available sociological, statistical, and ambient monitoring studies, the following variables were estimated: percentage of time spent in activities away from the residence such as shopping and working; proportion of the population following given living patterns; and typical benzene concentrations associated with each activity. The percentage of time spent in 1 year in various activities was multiplied by the associated benzene concentration and summed to determine an individual's total exposure.

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[*] The detection limit of current sampling techniques.

The resulting estimates are subject to considerable uncertainty in regard to: (1) the quantity of benzene emissions, (2) benzene production and consumption levels, (3) source locations, (4) control technologies employed, (5) deterioration of control technologies over time, (6) physical characteristics (e.g., stack height) of benzene sources, (7) population density in the vicinity of sources, (8) living patterns of the exposed population, and (9) relationship of ambient monitoring data to dispersion modeling estimates. Given these complex and variable factors, the accuracy of the estimates could not be assessed quantitatively. Nevertheless, the estimates, although not precise, approximate expected conditions.

Table I-1 summarizes results of the source-specific assessment. Urban exposures constitute the largest sources. Chemical manufacturing facilities are second, with more than 7 million people exposed over a wide range of exposure levels. Petroleum refineries are sources of benzene exposures for more than 5 million people.

For approximate comparison of different emission sources, exposures are calculated in similar units by multiplying the number of exposed population by the annual average benzene concentration within each range. These values were then summed for each emission source. Thus, the units become ppb-person-years (Table I-1). We assumed that people who use self-service gasoline are exposed to this emission source for 1.5 hours per year.

Table I-1

SUMMARY OF ESTIMATED POPULATION EXPOSURES TO ATMOSPHERIC BENZENE FROM SPECIFIC BENZENE EMISSION SOURCES[a]

Source	Number of People Exposed to Benzene Concentrations (ppb)[b]					Comparison Among Sources (10^6 ppb-person-years)
	8-hour Worst Case: 2.5-25.0 Annual average: 0.1-1.0	25.1-100.0 1.1-4.0	100.1-250.0 4.1-10.0	>250.0 > 10.0	Total[c]	
Chemical manufacturing	6,000,000	1,000,000	200,000	80,000	7,300,000	8.5
Coke ovens	300,000				300,000	0.2
Petroleum refineries	5,000,000	3,000			5,000,000	2.5
Solvent operations	d				--	--
Storage & distribution of gasoline	e				--	--
Automobile emissions - urban[f]	69,000,000	45,000,000			110,000,000	150.0
Gasoline service stations - urban[f]	20,000,000	900,000			21,000,000	12.0
People using self-service gasoline				g	37,000,000	1.6

---

[a] Assumes that people living in the vicinity of benzene sources spend 24-hours of each day in that location.

[b] To convert to μg/m^3, multiply each exposure level by 3.2; to estimate one-hour worst case concentrations multiply 8-hour worst case by 10.

[c] Population estimates are not additive vertically, because double-counting exists. Totals are rounded to two significant figures.

[d] Exact determination is impossible.

[e] Estimated at << 0.1 ppb annual average. The population exposed was not determined but is assumed to be very small.

[f] 8-hour worst case is estimated by multiplying each exposure level by 4.1.

[g] Estimated at 245 ppb for 1.5 hr/yr/person.

Source: SRI estimates.

The results presented in Table I-1 show that urban exposures have the highest weighted human exposures. Next are chemical manufacturing plants, followed by petroleum refineries. These results differ because they are weighted by the number of people exposed to a particular level of atmospheric benzene. Thus, they provide a useful basis for comparison and, assuming a linear dose-response relationship, are directly related to human health.

The total exposure for individuals living in the vicinity of benzene sources (assuming the several scenarios of living patterns discussed in Chapter X) is shown in Table I-2. When this exposure is compared with those shown in Table I-1, several significant differences are evident. The levels to which more than 90% in the lowest range are exposed have been increased sufficiently to place these people in the second range because benzene exposure levels for most activities considered (i.e., shopping, commuting, working) are higher than 1.0 ppb. Therefore, the weighted sum for all exposures is higher than the original estimate. This analysis indicates that living patterns affect annual average benzene exposures--generally by increasing those exposures because higher benzene exposures occur in nonresidential settings.

As indicated above, the estimates given in this report are subject to considerable uncertainty; they thus require further monitoring and sampling data for a more complete assessment. Despite the insufficiency of data, however, the fact remains that the population exposed is substantial. Potential health effects from the estimated exposures will be addressed in another report being prepared by the EPA Cancer Assessment Group.

Table I-2

SUMMARY OF ESTIMATED TOTAL EXPOSURES* OF PEOPLE
RESIDING IN THE VICINITY OF ATMOSPHERIC BENZENE SOURCES

Vicinity of Residence	Number of People Exposed					Comparison Among Sources†‡ (10^6 ppb-person-year)
	Annual Average Benzene Concentrations (ppb)				Total†	
	0.1-1.0	1.1-4.0	4.1-10.0	> 10.0		
Chemical manufacturing	3,900,000	3,100,000	200,000	80,000	7,300,000	10.0
Coke ovens	200,000	100,000			300,000	0.2
Petroleum refineries	3,250,000	1,750,000			5,000,000	4.5
Urban areas		110,000,000			110,000,000	250.0

---

*The term "total exposures" is used to mean the sum of an individual's exposure to atmospheric benzene from a variety of activities during a year. This assumes that people spend part of their time away from their residence, resulting in exposures to different benzene concentrations depending on their activity (i.e., commuting to work, shopping, traveling on personal business). Nonurban exposures are not included in this analysis but are expected to range from undetectable to 1.0 ppb.

†Rounded to two significant figures.

‡The median values shown in Table X-10 were used for this calculation instead of the mid-point of the ranges. This allows a better comparison with Table I-1.

Source: SRI estimates.

II BENZENE IN THE ENVIRONMENT

A. Introduction

The primary objective of this study has been to rank specific benzene emission sources by estimating the atmospheric exposure of the U.S. population to benzene from each source. The ranking of sources will serve as input for establishing regulatory priorities. Implied in this analysis is the assumption that individuals living near the sources spend 24-hours of each day in that location and they are only exposed to emissions from that source. However, because benzene sources are numerous and diverse, there is reason to believe that certain individuals have significantly different exposures from those estimated by this method and are exposed to emissions from more than one source. Therefore, after public review and comment on the initial draft of this study, a second objective was added to make first-cut estimates of total exposure to individuals living in the vicinity of benzene sources. Total exposure is the sum of the exposures to all benzene sources over a designated period (e.g., a day or a week).

This study is one in a series that SRI is conducting for EPA to estimate populations at-risk to selected pollutants. These studies are generally conducted on a quick-response basis to provide input to other, more inclusive studies. This study has not considered the degree of biological sorption of material. No attempt was required or has been made in this input report to assess potential health effects.

Atmospheric sources of benzene are widespread and include natural sources such as forest fires and man-made sources such as automobile emissions. Although benzene is not sampled regularly in any air quality monitoring program, some sampling data do exist. EPA has also conducted dispersion modeling that is applicable to most of the major sources. On the other hand, sample data of benzene concentrations in water, food, and soil are sparse, and those measurements that have been taken have been infrequent and inconsistent.

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Benzene is commercially produced mainly by petrochemical operations (92%) and on a much smaller level as a coke-oven by-product (8%). Total benzene production in 1976 was approximately 7500 x 10^6 lb (3400 x 10^6 kg) (SRI estimates). Benzene is a constituent of gasoline and crude oil. Pure benzene is used primarily in chemical manufacturing processes, and in solvent operations. Of all benzene used in chemical and solvent operations, more than 97% is used in chemical processing (SRI estimates).

For this report, seven sources of atmospheric benzene were evaluated: chemical manufacturing plants, coke ovens, self-service gasoline stations, petroleum refineries, solvent operations, storage and distribution of gasoline, and urban exposures related to automobile emissions and evaporation from gasoline stations. These sources have been identified as the major sources of atmospheric benzene (PEDCo, 1977; Johnson, 1977). Although oil spills and discharges represent a potentially significant source of benzene in the environment, the most significant of these occur in remote locations or along coastal areas where population density is low, and the benzene released to the atmosphere from each occurrence is very small. Potential human exposure to atmospheric benzene from oil spills and discharges appears to be negligible.

Because few quantitative data were available for this study, all estimates given here are subject to considerable uncertainty. This is related to: quantity of benzene emissions, benzene production and consumption level, source locations, control technology employed, deterioration of control technology over time, and dispersion modeling. The available monitoring data are summarized in the discussion of each source; however, because these data are insufficient, the accuracy of the monitoring results could not be quantitatively assessed. Quality control information was unavailable for much of these data. Comparisons of short-term ambient concentrations indicated by monitoring data with annual average ambient concentrations estimated from dispersion modeling are tenuous. In addition, meterological conditions and in-plant operating characteristics during a sampling period may differ significantly from average conditions. Even with these uncertainties, a comparison of monitoring data with dispersion modeling results suggests that the agreement between the two is sufficient to lend support to the modeled concentrations.

B. Nonatmospheric Benzene

It is not within the scope of this study to evaluate human exposures to benzene from water, food, or other environmental pathways. However, it is useful to review the available data to provide some basis for comparison.

Only limited data on benzene in water are available. A review of benzene sampling data by Howard and Durkin (1974) found that the few freshwater samples analyzed by that time showed only trace levels of benzene. For example, a 1972 EPA study cited in the report identified 53 organic chemicals, ranging from acetone to toluene, in the finished waters and organic waste effluents in 11 plants (of 60 sampled) discharging into the Mississippi River. Benzene was not detected in the effluents, but the trace detected in the finished waters suggested another source than effluent discharge.

A recent sampling of five benzene production or consumption plants by Battelle (1977a) found benzene levels in water ranging from < 1.0 to 179 ppb (plant effluent). The concentrations at 13 upstream and downstream sample locations in nearby receiving waters, however, ranged from < 1.0 to 13.0 ppb, with an average of 4.0 ppb.

A recent report by the National Cancer Institute (1977) noted benzene levels of 0.1 to 0.3 ppb in four U.S. city drinking water supplies. One measurement from a groundwater well in Jacksonville, Florida showed levels higher than 100 ppb. No indication is given in the report of the sampling methods or the analytical procedures. However, study of the behavior of benzene in the groundwater system and in the drinking water supply system is clearly warranted.

One possible source of benzene in the aquatic environment is from cyclings between the atmosphere and water (Mitre, 1976). Benzene is fairly volatile (high vapor pressure of 100 mmHg at 26°C) and has a relatively high solubility (1780 mg/L[*] at 25°C). Consequently, it is reasonable to believe that benzene will be washed out of the atmosphere with rainfall and then evaporated back into the atmosphere, causing a continuous recycling between the two media.

The distribution of benzene in the aquatic system is not well-known. Neely et al. (1974) demonstrated a relationship between octanol-water partition coefficients and bioaccumulation potential in fish. The partition coefficient for benzene, which is estimated to be very low, suggests that the bioaccumulation potential in fish is minimal. Benzene uptake by aquatic vegetation has not been studied.

Only one study of benzene levels in soil has been conducted. Battelle (1977a) sampled soils in the vicinity of five benzene consumption or production facilities. Their preliminary results from 14 samples showed levels ranging from < 1.0 to 191.0 ppb, with an average of 53.0 ppb. In most cases, the highest levels of benzene were found in samples taken closest to the plant. These results indicate that the potential for accumulation of benzene in the soil is significant.

Human exposure to benzene in food is not addressed in this report. We note, however, the following information: those few available data that quantify benzene levels in food (Chinn, personal communication, 1977) indicate that it occurs naturally in fruits, fish, vegetables, nuts, dairy products, beverages, and eggs. However, data on concentrations are only available for cooked meat, rum, and eggs (see Table II-1). A report by the National Cancer Institute (1977) estimated that an individual could ingest as many as 250 μg/day from these foods.

---

[*] L = liter.

Table II-1

ESTIMATED BENZENE LEVELS IN FOOD
(μg/kg)

Heat treated or canned beef	2
Jamaican rum	120
Irradiated beef	19
Eggs	2100

Source: National Cancer Institute (1977)

C. Chemical and Physical Properties of Benzene

Benzene, C_6H_6, is a nonpolar, nonreactive, highly refractive cyclic aromatic hydrocarbon. In benzene, the C-C bond is 1.38 Å long and the CH bond is 1.08 Å long (Ayers and Muder, 1964; MacKenzie, 1962). Under standard conditions, benzene is a clear, noncorrosive, colorless, and highly flammable liquid. Benzene possesses a characteristic odor, similar to that of gasoline. It is relatively soluble in water and is miscible with acetone, alcohol, chloroform, ether, carbon disulphide, carbon tetrachloride, glacial acetic acid, and oils. Pertinent physical properties of benzene are listed in Table II-2.

Benzene is quite thermodynamically stable because the resonance energy of its unsaturated bonds is due to the interaction of the six π electrons that form "doughnut" shaped electron orbitals above and below the plane of the ring.

Benzene solubility in water at 25°C is 1800 ppm (0.18 mg/g water) Variation of benzene solubility in water from 1730 to 1800 ppm has been noted (McAuliffe, 1963). The difference is believed to be attributable either to the temperature of the experiment or the precision of the technique. Both salting-in and salting-out (increase or decrease in solubility) phenomena have been observed for benzene in aqueous solution (Giacomelli, 1972). Benzene solubility in salt water and distilled water

Table II-2

PROPERTIES OF BENZENE

Constant	Value
Freezing point, °C	5.553
Boiling point, °C	80.100
Density, at 25°C, g/mL	0.8737
Vapor pressure at 26.075°C, mm Hg	100
Refractive index, n_D^{25}	1.49792
Viscosity (absolute) at 20°C, cP	0.6468
Surface tension at 25°C, dyn/cm	28.18
Critical temperature °C	289.45
Critical pressure, atm	48.6
Critical density, g/mL	0.300
Flash point (closed cup), °C	-11.1
Ignition temperature in air, °C	538
Flammability limits in air, vol%	1.5-8.0
Heat of fusion, kcal/mole	2.351
Heat of vaporization at 80.100°C, kcal/mole	8.090
Heat of combustion at constant pressure and 25°C (liquid C_6H_6 to liquid H_2O and gaseous CO_2), kcal/g	9.999
Solubility in water at 25°C, g/100 g water	0.180
Solubility of water in benzene at 25C, g/100 g benzene	0.05

Source: Ayers and Muder (1964).

have been compared, and the results show that solubility decreases as the salt content of water increases (Sutton and Calder, 1974). A similar decrease in solubility of the water soluble fraction (including benzene) from crude oil was observed (Lee, 1974). These observations reveal that benzene is less soluble in salt water than in fresh water.

The vapor pressure of benzene is an important property in assessing the benzene contamination in the gaseous phase. The vapor pressure of 100 mmHg at 26°C indicates that benzene exists environmentally only in the gaseous and the aqueous phases.

Benzene is highly stable. Consequently, chemical reactivity is limited unless the reactions take place under certain extreme conditions (and in the presence of the necessary reagents). When chemical reactions do take place, benzene behaves primarily as a nucleophilic agent, usually with substitution of individual hydrogen atoms rather than addition. The two most common substitutive reactions are nitration and sulfonation. In additive reactions, other reactive chemical agents are added to the unsaturated bonds. Three types of additive reactions are most common: oxidation, hydrogenation, and halogenation.

The general environmental fate of benzene can be assessed by examining the degradation processes of oxidation, hydrolysis, photolysis, and microbial decomposition. Hydrolysis and microbial decomposition occur primarily in the aqueous phase, whereas oxidation and photolysis can occur in both the aqueous and the gaseous phases.

Benzene can be oxidized to a number of different products in the presence of catalysts or at elevated temperatures and pressures. Under extreme conditions, benzene has been observed to oxidize completely to water and carbon dioxide. In the environment, such extreme conditions rarely exist. Thus, it can be concluded that degradation of benzene by oxidation is probably negligible. Oxidation in the emission pathways from chemical plants and refineries is conceivable, but no such observations have been reported.

The benzene ring does not undergo reaction with water or hydroxyl ions (OH^-) unless substituted with a significant number of strong electronegative groups, or at elevated temperature and pressure. Thus, hydrolysis in the environment is assumed to be minimal.

Several studies have investigated the wavelength absorption properties of benzene. No appreciable amounts of light at wavelength longer than 280 nm (2800Å) were directly absorbed by benzene dissolved in cyclohexane. A slight shift, however, in wavelength absorption would be more representative of environmental media, such as dissolution in water or adsorption on particular matter. Chien (1965) reported the ultraviolet absorption spectra of liquid benzene in the presence of oxygen under 1 atmosphere. Noyes et al. (1966) found that gaseous benzene only absorbs light at 275 nm or less. Because the atmospheric ozone layer effectively filters out wavelengths less than 290 nm, it appears that direct excitative photolytic reaction of benzene in the environment is unlikely, unless a substantial wavelength shift occurs in the presence of other media. Indirect excitation of benzene may be possible in the presence of certain sensitizers in the water or soil.

Photolysis by light with a wavelength of less than 290 nm of benzene in the vapor phase and in oxygenated aqueous solution has been reported. Two types of products, 2-formyl-4H-pyran and cyclopentadiene-carboxaldehyde result (Luria and Stein, 1970; Kaplan et al., 1971). Matsuura and Omura (1974) have reviewed several investigations where atomic oxygen that had been photochemically generated from various sources reacted with benzene to form phenol. Atomic oxygen is generated, for instance, from the photodecomposition with nitrogen dioxide, which is frequently found in high concentration in heavily polluted air (Altshuller, 1971). Laboratory results conclude that benzene is not completely inert under smog conditions (Laity et al., 1973; Stephens, 1973).

The microbial degradation of benzene has received some attention in recent years and it is conceivable that biodegradation of benzene probably occurs under environmental conditions. Benzene has been found to biodegrade in a waste treatment plant, with the rate of degradation determined by the incubation period and acclimation of the microorganisms. It is safe to conclude, therefore, that benzene can be degraded--but at a very slow rate.

In summary, oxidation and hydrolysis of benzene in the environment are unlikely. Photolysis is possible in the natural environment, but the photolysis rate depends on wavelength adsorption and the presence of sensitizers. In a heavily polluted atmosphere, atomic oxygen may cause photochemical decomposition of benzene. Biodegradation of benzene in the environment is also possible, but the degradation rate is quite slow.

III CHEMICAL MANUFACTURING FACILITIES

A. Sources

In this section, generation of benzene emissions from the manufacturing of chemical compounds will be addressed. Producer companies of various compounds (excluding solvents) are listed in Table III-1; their locations and 1976 capacity productions are also included in the table. The Gulf Coast has the highest density of these benzene-consumption facilities.

Benzene is used commercially as an intermediate agent in the production of many chemical compounds. The emissions of benzene from such industrial uses are potentially significant sources of atmospheric benzene. Total U.S. consumption of benzene in 1975 was 108.4 x 10^7 gal (4.1 x 10^6 m^3) (Anderson, 1976). Figure III-1 illustrates the benzene derivatives and their uses. Primary use involves the manufacture of such chemicals as nitrobenzene, ethylbenzene, maleic anhydride, cumene, phenol, chlorobenzene, cyclohexane, and detergent alkylate. Appendix A contains flow diagrams for some of these processes.

Some atmospheric monitoring data were collected in the vicinity of five benzene-consumption facilities by Research Triangle Institute (RTI) (1977). Grab samples were collected for periods ranging from 25 minutes to 12 hours, both on the plant property and within 1 km of the plant boundary. Benzene concentrations ranged from 0.5 to 58.4 ppb. The average benzene concentration for each location is shown in Table III-2. Complete quality control information is unavailable for these samples.

Emissions from chemical manufacturing facilities contain many chemical compounds in addition to benzene; some of these compounds have demonstrated toxic and/or carcinogenic properties. Although few data exist about the composition of emissions from various processing facilities, Table III-3 contains a partial list of the major emissions. Individuals

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Table III-1

LOCATIONS AND CAPACITIES OF PLANTS USING BENZENE AS AN INTERMEDIARY AGENT IN THE MANUFACTURE OF VARIOUS CHEMICAL COMPOUNDS*

STATE	LOCATION	COMPANY	CAPACITY PRODUCTION JANUARY 1, 1976 (millions of kg)										
			NITRO-BENZENE	ANILINE	ETHYL-BENZENE	STYRENE	MALEIC ANHYDRIDE	CUMENE	PHENOL	MONO-CHLORO-BENZENE	DICHLORO-BENZENE (O- and P-)	CYCLO-HEXANE	DETERGENT ALKYLATE (Linear and Branch)
ALABAMA	TUSCALOOSA	REICHHOLD CHEM., INC.							68				
CALIFORNIA	CARSON	WITCO CHEM.											25
	EL SEGUNDO	STD. OIL CO. OF CALIF.						45					
	IRWINDALE	SPECIALTY ORGANICS, INC.									1		
	RICHMOND	STD. OIL CO. OF CALIF.							26				100
	SANTA FE SPRINGS	FERRO CORP.							N.A.				
DELAWARE	DELAWARE CITY	STD. CHLORINE CHEM CO., INC.								34	27^b		
GEORGIA	CARTERSVILLE	CHEM. PRODUCTS CORP									10^a		
ILLINOIS	BLUE ISLAND	CLARK OIL & REFINING						50	40				
	CICERO	KOPPERS CO., INC.					.5						
	MORRIS	REICHHOLD CHEM., INC.					27						
	SAUGET	MONSANTO	5							52	13		
KANSAS	EL DORADO	SKELLY OIL CO.						61	63				
KENTUCKY	ASHLAND	ASHLAND OIL, INC.						160					
LOUISIANA	BATON ROUGE	FOSTER GRANT CO.			440	372							
	CARVILLE	COS-MAR, INC.			327	272							
	CHALMETTE	TENNECO, INC.			12								
	GEISMAR	RUBICON CHEM., INC.	34	26									
	PLAQUEMINE	GEORGIA PACIFIC CORP.							120				
	WELCOME	GULF OIL CORP.			250	238							
MARYLAND	BALTIMORE	CONTINENTAL OIL CO.											98
MASSACHUSETTS	MALDEN	SOLVENT CHEM. CO., INC.								N.A.	1^a		
MICHIGAN	MIDLAND	DOW CHEMICAL			250	182		4.6	18	136	29		
MISSISSIPPI	PASCAGOULA	FIRST MISSISSIPPI CORP.	81	46									
MISSOURI	ST. LOUIS	MONSANTO					48						
NEVADA	HENDERSON	MONTROSE CHEM.CORP. OF CAL.								32			
NEW JERSEY	BOUND BROOK	AMERICAN CYANAMID	38	27									
	BOUND BROOK	UNION CARBIDE							68				
	ELIZABETH	REICHHOLD CHEM., INC.					14						
	FORDS	TENNECO, INC.					12						
	GIBBSTOWN	E. I. du PONT	91	50									
	KEARNY	STD. CHLORINE CHEM. CO.									7^a		
	WESTVILLE	TEXACO, INC.						118					

Table III-1 (Continued)

STATE	LOCATION	COMPANY	CAPACITY PRODUCTION JANUARY 1, 1976 (millions of kg) NITRO-BENZENE	ANILINE	ETHYL-BENZENE	STYRENE	MALEIC ANHYDRIDE	CUMENE	PHENOL	MONO-CHLORO-BENZENE	DICHLORO-BENZENE (O- and P-)	CYCLO-HEXANE	DETERGENT ALKYLATE (Linear and Branch)
NEW YORK	NIAGARA FALLS	ICC INDUSTRIES, INC.								N.A.	N.A.		
	NIAGARA FALLS	OCCIDENTAL PETROLEUM								7			
	NIAGARA FALLS	SOLVENT CHEM. CO.								N.A.	9		
	SYRACUSE	ALLIED CHEM. CORP.								11	8		
OHIO	HAVERHILL	UNITED STATES STEEL							90				
PENNSYLVANIA	BEAVER VALLEY	ARCO/POLYMERS, INC.				200							
	BRIDGEVILLE	KOPPERS CO., INC.					15						
	CLAIRTON	UNITED STATES STEEL							N.A.				
	FRANKFORD	ALLIED CHEMICAL CORP.							250				
	NEVILLE ISLAND	UNITED STATES STEEL					18						
	PHILADELPHIA	GULF OIL CORP.						206				98	
PUERTO RICO	GUAYAMA	PHILLIPS PETROLEUM										200	
	PENUELAS	COMMONWEALTH OIL			73							118	
	PENUELAS	UNION CARBIDE CORP						290	90				
TEXAS	BAYTOWN	EXXON CORP										118	
	BEAUMONT	E. I. du PONT	141	91									
	BEAUMONT	UNION OIL CO. OF CALIFORNIA										100	
	BIG SPRING	AMERICAN PETROFINA			20	41						36	
	BORGER	PHILLIPS PETROLEUM										118	
	CHOCOLATE BAYOU	MONSANTO						295	227				102
	CORPUS CHRISTI	COASTAL STATES GAS						64					
	CORPUS CHRISTI	SUN OIL CO.			43	36		114					
	CORPUS CHRISTI	UNION PACIFIC CORP										65	
	FREEPORT	DOW CHEMICAL			848	849							
	HOUSTON	ARCO/POLYMERS, INC.			45	45							
	HOUSTON	THE CHARTER CO.			18								
	HOUSTON	JOE OIL, INC.											
	HOUSTON	THE MERICHEM CO.							N.A.				
	HOUSTON	PETRO-TEX CHEM CORP.					23						
	ODESSA	EL PASO NATURAL GAS			125	68							
	OYSTER CREEK	DC [illegible] CHEMICAL							187				
	PHILLIPS	PHILLIPS PETROLEUM CO.										209	
	PORT ARTHUR	ARCO/POLYMERS, INC.			200								
	PORT ARTHUR	GULF OIL CORP						206					
	PORT ARTHUR	TEXACO						118					
	SEADRIFT	UNION CARBIDE CORP			156	136							
	SWEENEY	PHILLIPS PETROLEUM CO.										251	

Table III-1 (Concluded)

STATE	LOCATION	COMPANY	CAPACITY PRODUCTION JANUARY 1, 1976 (millions of kg) NITRO-BENZENE	ANILINE	ETHYL-BENZENE	STYRENE	MALEIC ANHYDRIDE	CUMENE	PHENOL	MONO-CHLORO-BENZENE	DICHLORO-BENZENE (O- and P-)	CYCLO-HEXANE	DETERGENT ALKYLATE (Linear and Branch)
TEXAS	TEXAS CITY	MARATHON OIL CO.						86					
	TEXAS CITY	MONSANTO			1450[c]	590							
	TEXAS CITY	STANDARD OIL (INDIANA)			430	382		28					
WEST VIRGINIA	CHARLESTON	UNION CARBIDE CORP											58
	FOLLANSBEE	KOPPERS CO., INC.								N.A.			
	MOUNDSVILLE	ALLIED CHEM CORP.	25				27						
	NATRIUM	PPG INDUSTRIES, INC.								41	23		
	NEW MARTINSVILLE	MOBAY CHEM CORP.	61	46									
	WILLOW ISLAND	AMERICAN CYANAMIDE	27	22									
WASHINGTON	ANACORTES	STIMSON LUMBER CO.							N.A.				
	KALAMA	KALAMA CHEMICAL							26				
TOTAL			483	314	3894	3211	189	1720	1252	313	120	2706	393

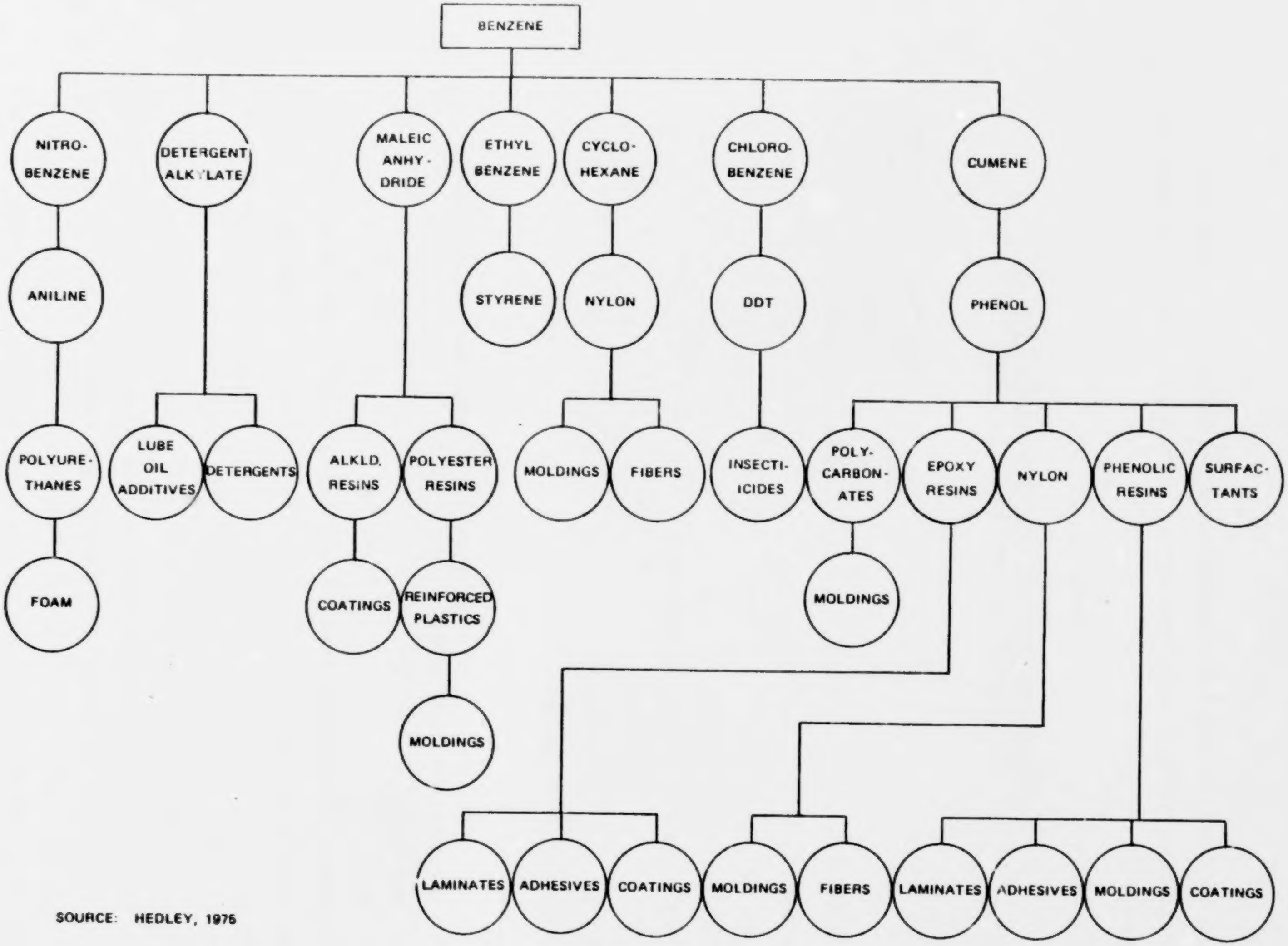
* SOURCE SRI, 1976 DIRECTORY OF CHEMICAL PRODUCERS, as cited in PEDCO, 1977

N.A. - NOT AVAILABLE

a. PRODUCTION CAPACITY FOR O-DICHLOROBENZENE ONLY

b. PRODUCTION CAPACITY FOR P-DICHLOROBENZENE ONLY

c. 1976 DATA SHOWED COMBINED ESTIMATES OF ETHYLBENZENE PRODUCTION AT CHOCOLATE BAYOU, TEXAS AND AT TEXAS CITY, TEXAS. 1977 SRI ESTIMATES SHOW ETHYLBENZENE PRODUCTION ONLY AT THE TEXAS CITY PLANT.


BENZENE
NITRO-BENZENE
DETERGENT ALKYLATE
MALEIC ANHY-DRIDE
ETHYL BENZENE
CYCLO-HEXANE
CHLORO-BENZENE
CUMENE
ANILINE
STYRENE
NYLON
DDT
PHENOL
POLYURE-THANES
LUBE OIL ADDITIVES
DETERGENTS
ALKLD. RESINS
POLYESTER RESINS
MOLDINGS
FIBERS
INSECTI-ICIDES
POLY-CARBON-ATES
EPOXY RESINS
NYLON
PHENOLIC RESINS
SURFAC-TANTS
FOAM
COATINGS
REINFORCED PLASTICS
MOLDINGS
MOLDINGS
LAMINATES
ADHESIVES
COATINGS
MOLDINGS
FIBERS
LAMINATES
ADHESIVES
MOLDINGS
COATINGS

SOURCE: HEDLEY, 1975

FIGURE III-1. BENZENE DERIVATIVES AND THEIR USES

residing in the vicinity of chemical manufacturing facilities are, therefore, exposed to a wide variety of chemical compounds in addition to benzene.

Table III-2

ATMOSPHERIC BENZENE CONCENTRATIONS SAMPLED AT BENZENE-CONSUMPTION FACILITIES

Location	Company	Number of Samples	Average Sampling Time (min)	Average Benzene Concentration (ppb)
S. Charleston, WV	Union Carbide	3	100	34
Freeport, TX	Dow	3	100	14
La Porta, TX	Dupont	3	110	0.8
Bound Brook, NJ	American Cyanamid	1	44	2.8
Fords, NJ	Tenneco	1	44	0.9
Geismar, LA	Rubicon*	6	740	0.6
Plaquemine, LA	Georgia Pacific*	11	660	0.9

---

*Samples taken in the vicinity of industrial complexes that have known benzene-consumption facilities.

Source: RTI (1977).

To assess the ambient benzene concentrations in the vicinity of chemical manufacturing facilities, two factors must be estimated: benzene emission rates at each location; and atmospheric dispersion of benzene in the vicinity of the plants. The emission rates can be estimated if the emission factors and total production are available. Table III-4 gives the emission factors used in the analysis and emission characterization. The emission factors were selected to represent averages. Because little is known about benzene emissions from chemical manufacturing facilities, these emission factors are considered order-of-magnitude estimates. Maleic anhydride and aniline have the highest emission factors related to the specific manufacturing processes and reaction kinetics of each compound.

Table III-3

MAJOR CHEMICAL COMPOUNDS OTHER THAN BENZENE EMITTED FROM CHEMICAL MANUFACTURING FACILITIES

Process	Reference	Compound
Aniline	2	Aniline Nitrobenzene
Chlorobenzene	4	Chlorobenzene Dichlorobenzene Trichlorobenzene o-, m-, and p- dichlorobenzene Chlorine Hydrochloric acid Ferric chloride
Ethylene/styrene	3	Methane Ethane Ethylene Hydrochloric acid Toluene Ethylbenzene Styrene di- and triethyl benzenes
Linear alkylate	4	n parafins (C_{10} - C_{14} range) Allyl chloride Linear alkyl benzene Hydrochloric acid Olefins Linear alkylate Hydrogen fluoride
Maleic anhydride	1	Maleic acid Formaldehyde Formic acid Acid aldehyde Xylene
Nitrobenzene	2	Nitrobenzene Dinitrophenol Other dinitro and trinitro compounds

---

1. Weber, personal communication, 1978.
2. Beck, personal communication, 1978.
3. Mascone, personal communication, 1978.
4. Schumaker, personal communication, 1978.

Table III-4

EMISSION FACTORS AND CHARACTERIZATIONS
FOR BENZENE-CONSUMPTION PLANTS

Chemical	Emission Factor (10^{-3} kg of benzene/kg of product)	Emission Characterization
Aniline[a]	23.60	Fugitive
Cumene[b]	0.25	Fugitive
Cyclohexane[a]	2.80	Fugitive
Detergent alkylate[a] (linear and branched)	2.20	Fugitive
Dichlorobenzene (p- and o-)[b]	8.60	Chlorinator, PDCD recovery system
Ethylbenzene[b]	0.62	Scrubber-vent
Maleic anhydride[b]	96.70	Product recovery scrubber
Monochlorobenzene[b]	3.50	Unknown
Nitrobenzene[b]	7.00	Point absorber
Phenol[b]	1.00	Unknown
Styrene[b]	1.50	Collection vent, emergency vent

---

[a] SRI estimates.

[b] PEDCo estimates.

The atmospheric dispersion of benzene is more difficult to assess.* Simply, source characteristics (e.g., stack dimensions) and meteorological conditions greatly influence the dispersion of benzene in the vicinity of the plants. Youngblood (1977a, 1978) made rough dispersion estimates from very limited data on source characteristics. He classified the processes according to three source categories: A--ground-level point source (effective stack height, 0 m); B--building source (effective stack height, 10 m); and C--elevated point source (effective stack height, 20 m). Emission rates were then calculated for each process by assuming a maximum production rate. Ambient ground-level concentrations were derived manually from Turner's workbook. One-hour worst-case concentrations were derived with the following meteorological conditions assumed: wind speed, 4 m/s; stability class, neutral (Pasquill Gifford "D"). For source category B, the results from Turner's workbook were adjusted to account for the initial dispersion of the pollutant in the building cavity. The one-hour estimates were then converted to 8-hour worst-case estimates (by multiplying by 0.5). The results of the dispersion modeling by Youngblood are given in Table III-5.

B. Methodology

Each chemical manufacturing plant has different production rates, chemical processes, geographic locations, pollution control technology, and meteorological conditions. Thus, detailed dispersion calculations are impractical, given the scope of the study. A simple method of assessment was therefore developed to allow for comparative analysis. Variations in geographic locations and meteorological conditions were not considered in the analysis. The results are not precise: rather, they provide a reasonable estimate of atmospheric benzene concentrations.

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*Battelle-Columbus has monitored benzene concentrations in the vicinity of chemical manufacturing facilities. These data are now in draft form and should be available in the near future.

Table III-5

ROUGH ESTIMATES OF AMBIENT GROUND-LEVEL BENZENE CONCENTRATIONS (8-HOUR AVERAGE)*

Source	Emission Rate (g/s)	Source Category	Concentration ($\mu g/m^3$) at Given Distance					
			150 m	300 m	450 m	600 m	750 m	1600 m
Maleic anhydride	139.0	C	700	5000	5000	3900	2900	1100
Styrene	7.49	A	3800	1100	530	330	220	68
		B	850	460	290	210	160	55
Phenol from cumene	10.8	C	54	390	390	300	230	89
Benzene	0.179	A	90	26	13	8	5	2
		B	20	11	7	5	4	1
Cumene	2.34	A	1200	340	170	100	70	21
		B	260	140	91	66	49	17
Phenol from benzene	0.0691	A	35	10	5	3	2	1
		B	8	4	3	2	1	<1
		C	<1	2	2	2	1	<1
Nitrobenzene	31.20	A	16000	4500	2200	1400	940	280
		B	3500	1900	1200	870	650	230
		C	160	1100	1100	870	650	250
Ethyl benzene	16.60	A	8500	2400	1200	730	500	150
		B	1900	1000	650	460	350	120
Phenol from toluene	2.42	A	1200	350	170	110	73	21
		B	270	150	94	68	51	17
Chlorobenzene	15.10	A	7700	2200	1100	660	453	140
		B	1700	940	590	420	320	110
		C	76	540	540	420	320	120
o-dichlorobenzene	3.60	A	1800	500	250	160	110	32
		B	400	220	140	100	75	26
		C	18	130	130	100	75	28
p-dichlorobenzene	6.20	A	3200	900	440	270	190	39
		B	700	380	240	180	130	46
		C	31	220	220	170	130	49

---

* This is a worst-case estimate. It may be multiplied by 0.04 to give rough estimates of annual average concentrations.

Key to Source Categories: A--ground-level point source: B--building source; C--elevated point source.

Source: Youngblood, 1977a.

A single dispersion curve was constructed and applied to all chemical manufacturing facilities, based on their emission rates. The derivation of this methodology is discussed below.

As shown in Table III-5, ambient benzene concentrations in the vicinity of chemical manufacturing plants vary significantly in relation to the characteristics of the emission sources. Exhaust gas temperature, which is important in determining near-source concentrations, was not considered. Because of the generally high concentrations estimated at 1.6 km (the maximum distance modeled in that analysis), Youngblood (1977b, 1978) extended his model calculations to a distance of 20 km with an emission rate of 100 g/s for each source category (see Table III-6).

The results of Youngblood's analysis are shown in Figure III-2. The ground-level (A) and building (B) sources are highest near the plant and decrease rapidly with distance. The elevated point source (C), however, shows low initial concentrations that increase to a peak followed by a decline. Although the differences due to source category are considerable at 150 m, the differences decrease rapidly with distance. Even as close as 300 m, the differences are within the range of uncertainty normally associated with dispersion calculations. In addition, distances less than 300 m are likely to be within the plant perimeter or to have low population densities. A single dispersion curve (Curve M in Figure III-2) was therefore developed to represent all three source categories, as suggested by Youngblood (1977b). This curve was derived by averaging the high and low values of the three emission source categories at each calculated distance. The resulting concentrations estimated by this method are shown in Table III-7.

Table III-6

ROUGH ESTIMATES OF AMBIENT GROUND-LEVEL BENZENE CONCENTRATIONS (8-HOUR-AVERAGE)* PER 100 g/s EMISSION RATE

Source Category	Concentrations ($\mu g/m^3$)											
	0.15 km	0.3 km	0.45 km	0.6 km	0.75 km	1.6 km	2.5 km	4.0 km	6.0 km	9.0 km	14.0 km	20.0 km
A	51,000	14,000	7,000	4,500	3,000	900	440	220	120	62	34	20
B	11,000	6,100	3,800	2,800	2,100	740	370	220	120	62	34	20
C	510	3,500	3,500	2,800	2,100	800	410	220	120	62	34	20

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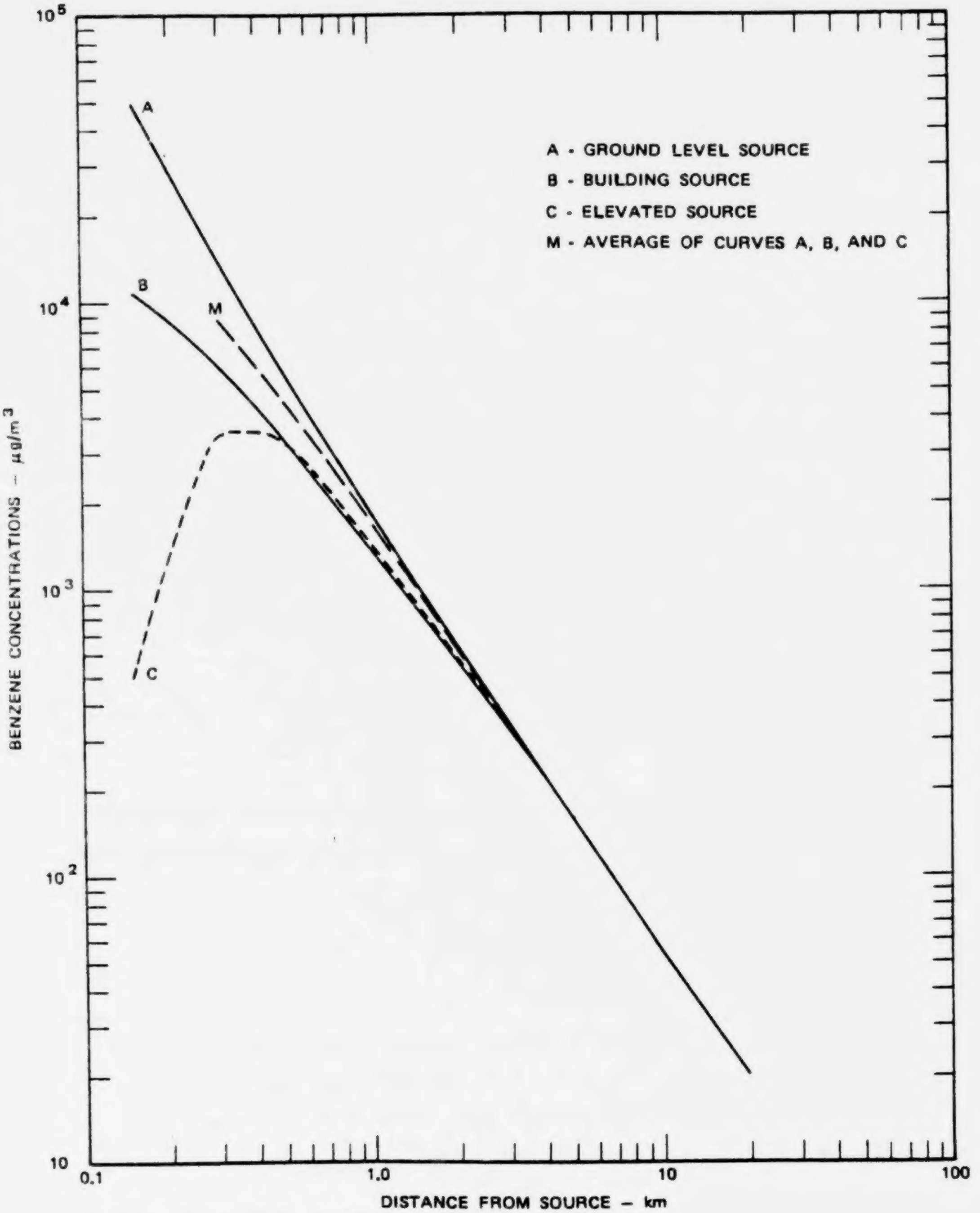
[*] To give rough estimates of annual average concentrations, multiply by 0.04; to convert to ppb, divide by 3.2.

Source: Youngblood (1977b, 1978).



*Based on an emission rate of 100 g/s

Source: After Youngblood, (1977b)

FIGURE III-2. DISPERSION MODELING RESULTS FOR EACH TYPE OF SOURCE CATEGORY*

Table III-7

ESTIMATES OF 8-HOUR WORST CASE[*] BENZENE CONCENTRATIONS BASED ON AVERAGE OF THREE EMISSION SOURCE CATEGORIES

Distance (km)	Concentration ($\mu g/m^3$)[+]
0.30	8800
0.45	5200
0.6	3600
0.75	2600
1.6	820
2.5	400
4.0	220
6.0	120
9.0	62
14.0	34
20.0	20

---

[*] To convert to annual average estimates, multiply concentrations by 0.04.

[+] To convert to ppb, divide concentrations by 3.2.

Source: Youngblood (1977b, 1978).

Regression analysis was used to develop an equation to characterize the single dispersion curve (Curve M). Equation (3.1) was derived from that analysis:

$$C = 1648\ D^{-1.48} \tag{3.1}$$

where, C is the 8-hour worst-case benzene concentration in $\mu g/m^3$, and D is the distance from the source in km. Because Equation (3.1) is only valid for an emission rate of 100 g/s, a normalized equation is given as follows:

$$C = 16.48\ E_a D^{-1.48} \tag{3.2}$$

where, E_a in g/s, is the emission rate for the location of interest.

The annual average concentration can be estimated by including a multiplier of 0.04 in the equation. Thus, the equation becomes:

$$C = 0.659\, E_a D^{-1.48} \tag{3.3}$$

In this study, the ranges of benzene concentrations that follow and that apply to all sources have been established for the sake of uniformity:

0.1 - 1.0 ppb
1.1 - 4.0 ppb
4.1 - 10.0 ppb
> 10.0 ppb

A computer program was developed to estimate the people exposed to concentrations within each range at each location. Equation (3.3) was rearranged as follows to determine the distance at which the specified concentrations are found:

$$D_i = 0.754 \left(\frac{E_a}{C_i} \right)^{0.6757} \tag{3.4}$$

where, C_i is the specified annual average concentration (i.e., 0.1, 1.0, 4.0, and so on; input data, however, are in $\mu g/m^3$); D_i is the distance in kilometers at which the specified concentration is found; and E_a is the emission rate in grams per second at that location.

The population residing within a circle of radius D_i was then estimated by the following equation:

$$P_i = d\, \pi\, D_i^2 \tag{3.5}$$

where, d is the city or state population density, and P_i is the population exposed to concentration C_i or greater.

The main assumptions in this analysis are that:

- The benzene source is in the center of the city (if the city has a population greater than 25,000).
- The maximum allowable radius is 20 km.
- The population density is uniform over the exposed area.
- When a city has more than one plant, the plants are colocated, and their corresponding emission rates are summed.
- If the city has a population of less than 25,000, state density is used.

To accommodate these assumptions, the following steps were included in the computer program. The radius of each city was determined by Equation (3.6):

$$D_c = \left(\frac{P_c}{\pi d_c} \right)^{1/2} \qquad (3.6)$$

where, D_c is the estimated radius of the city; P_c is the population of the city (1970 Bureau of Census data); and d_c is the average city density (1970 Bureau of Census data available for cities of population greater than 25,000).

When D_i calculated from Equation (3.4) is greater than D_c, or when no city density is available, Equation (3.7) is substituted for Equation (3.5) to calculate the exposed population on the basis of state density.

$$P_i = P_c + d_s \pi (D_i^2 - D_c^2) \qquad (3.7)$$

where, d_s is average state population density; D_i is the distance at which concentrations C_i is found; D_c is the radius of the city calculated in Equation (3.6); and P_i is the population exposed to concentration C_i or greater. P_c and D_c equal 0 when no city density is available.

Because the dispersion modeling results are unverified at distances greater than 20 km from the source location, the computer program automatically cut off calculations when (1) a distance of 20 km was attained and calculated the concentration (C_i) at 20 km, or when (2) the estimated benzene concentration dropped below 0.1 ppb.

The cumulative population totals resulting at distance D_i were then automatically subtracted from those at distance D_{i-1}, and the total population within each range of concentrations was printed out. For example, for range 0.1 to 1.0 ppb, the program subtracted $P_{1.0}$ (a smaller number) from $P_{0.1}$ (a larger number). In other words, $P_{0.1}$ is the population exposed to concentrations of 0.1 ppb or greater; $P_{1.0}$ is the total population exposed to concentrations of 1.0 ppb or greater. By subtracting the two values, the total population exposed to concentrations between 0.1 and 1.0 ppb is determined.

For locations with fewer than three chemical manufacturing facilities, an area of 0.5 km^2 (a circular area with a radius of 400 m) was assumed to be within the plant boundary. No exposed population was estimated within this area. For locations with three or more facilities, an area of 0.8 km^2 (a circular area with a radius of 500 m) was assumed to be within the plant boundary.

Emission rates were estimated for each plant, based on the production estimates contained in Table III-1 and the emission factors in Table III-4. Because actual production data are unobtainable, capacity production and 24-hour (365 days) operation were assumed. Appendix B, Table B-1, lists the estimated emission rates for each chemical manufacturing facility. The emissions of benzene from chemical manufacturing facilities were assumed to be the sole contributors of benzene to the atmosphere in the vicinity of the facility.

C. Exposures

Ambient benzene concentrations and the exposed population for each source location were estimated, based on the methodology described above. Table B-2 in Appendix B presents the results of this analysis for each facility location.

Table III-8 presents the estimated population exposed to specified levels of atmospheric benzene for each state. More than 7 million people are exposed to annual average benzene concentrations of 0.1 ppb or greater. The largest number of those exposed is found in Pennsylvania, Texas, and

Table III-8

ESTIMATED POPULATION EXPOSED TO BENZENE FROM CHEMICAL MANUFACTURING FACILITIES, BY STATE

State	Population Exposed[*] to Benzene (ppb)[+]			
	0.1-1.0	1.1-4.0	4.1-10.0	> 10.0
Alabama	20,000	500	-	-
California	110,000	4.400	400	-
Delaware	20,000	1,500	200	-
Georgia	7,000	200	-	-
Illinois	180,000	86,000	13,000	1,700
Kansas	4,000	80	-	-
Kentucky	20,000	-	-	-
Louisiana	140,000	42,000	5,600	1,100
Maryland	500,000	15,000	1,000	-
Massachusetts	3,000	-	-	-
Michigan	70,000	26,000	3,000	400
Mississippi	20,000	7,000	1,000	30
Missouri	20,000	400,000	100,000	50,000
Nevada	10,000	400	-	-
New Jersey	1,100,000	110,000	23,000	8,800
New York	180,000	7,000	-	-
Ohio	3,000	100	-	-
Pennsylvania	2,200,000	350,000	40,000	13,000
Texas	1,500,000	200,000	32,000	7,700
Washington	1,000	-	-	-
West Virginia	110,000	8,500	630	-
Puerto Rico	200,000	22,000	4,600	80
Total Exposed Population[‡]	6,000,000	1,000,000	200,000	80,000

---

[*] Totals for each state are rounded to two significant figures.

[+] Annual average concentrations; to convert to 8-hour worst case, multiply by 25; to convert to $\mu g/m^3$, multiply by 3.2; a dash (-) signifies that no exposed population was estimated by our method for the annual average concentrations listed. There may be some population exposed to those concentrations for shorter periods of time.

[‡] Totals are rounded to one significant figure.

Source: SRI estimates.

New Jersey. These three states account for 75% of the total population exposed to benzene from chemical manufacturing facilities.

Chemical manufacturing facilities are responsible for all point-source exposures to the general population greater than 4.0 ppb. Because our computer program is limited to estimating exposed population rather than specific concentrations, predicted concentrations must be calculated separately. To provide an upper boundary for our exposure estimates, the predicted dispersion curves for the four largest uncontrolled chemical manufacturing facilities are shown in Figure III-3. The facilities were selected for two reasons: (1) a high benzene emission rate (greater than 50 g/s, see Table B-2, Appendix B); (2) a large exposed population estimated at high concentrations (Reichold Chemicals, Elizabeth, New Jersey). A plant boundary of 450 m from the source was assumed. The highest concentrations are found in the vicinity of the Monsanto maleic anhydride plant in St. Louis. Annual average concentrations are in excess of 10 ppb as far as 2 km from the source. At the plant boundary, the estimated annual average concentration is 96 ppb. For comparison, estimated urban annual average concentrations related to automobile emissions generally range between 1 and 4 ppb. The lowest concentrations of those facilities plotted are found in the vicinity of the Reichold Chemicals maleic anhydride plant in Elizabeth, New Jersey. Those annual average concentrations range from 28 ppb at the plant boundary to 0.1 ppb at 20 km from the source.

Short-term high level exposures may also be important in affecting risk[*] to an individual. Figure III-4 compares annual average with 8-hour worst case concentrations. Note that both facilities show 8-hour worst case concentrations above 1.0 parts per million (ppm) outside the plant boundary, with 1-hour peak levels a factor of 10 higher than the 8-hour concentrations. For the two facilities shown on Figure III-4, the 1-hour

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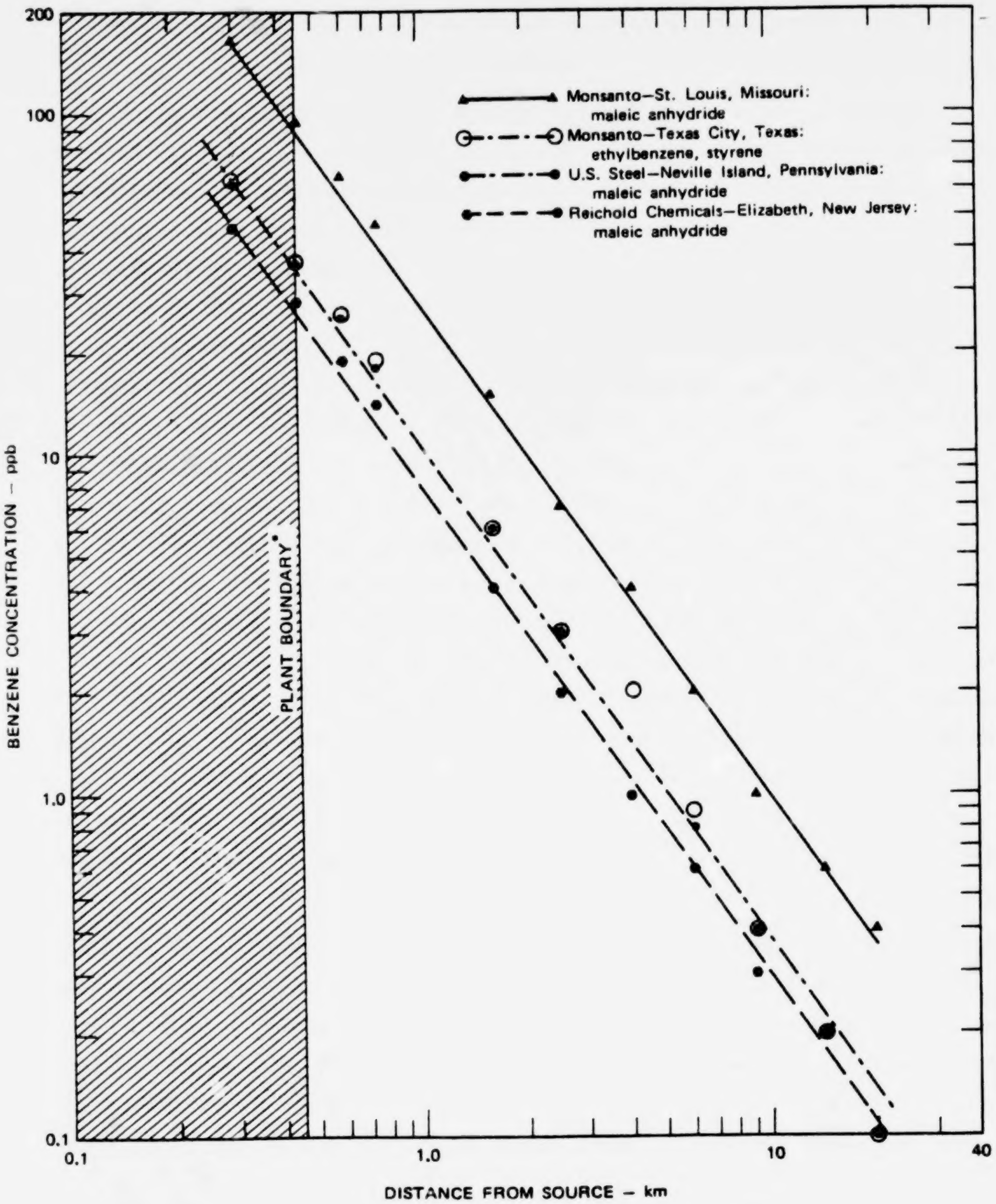
[*] The assumption of a linear dose-response, however, requires that higher concentrations for short periods have no higher risk associated with them.



* Assumed

** The four facilities having the largest benzene emissions and/or the largest number of exposed population at high concentrations.

Source: SRI estimates based on dispersion modeling.

FIGURE III-3. PREDICTED ANNUAL AVERAGE BENZENE CONCENTRATIONS IN THE VICINITY OF SELECTED** CHEMICAL MANUFACTURING FACILITIES

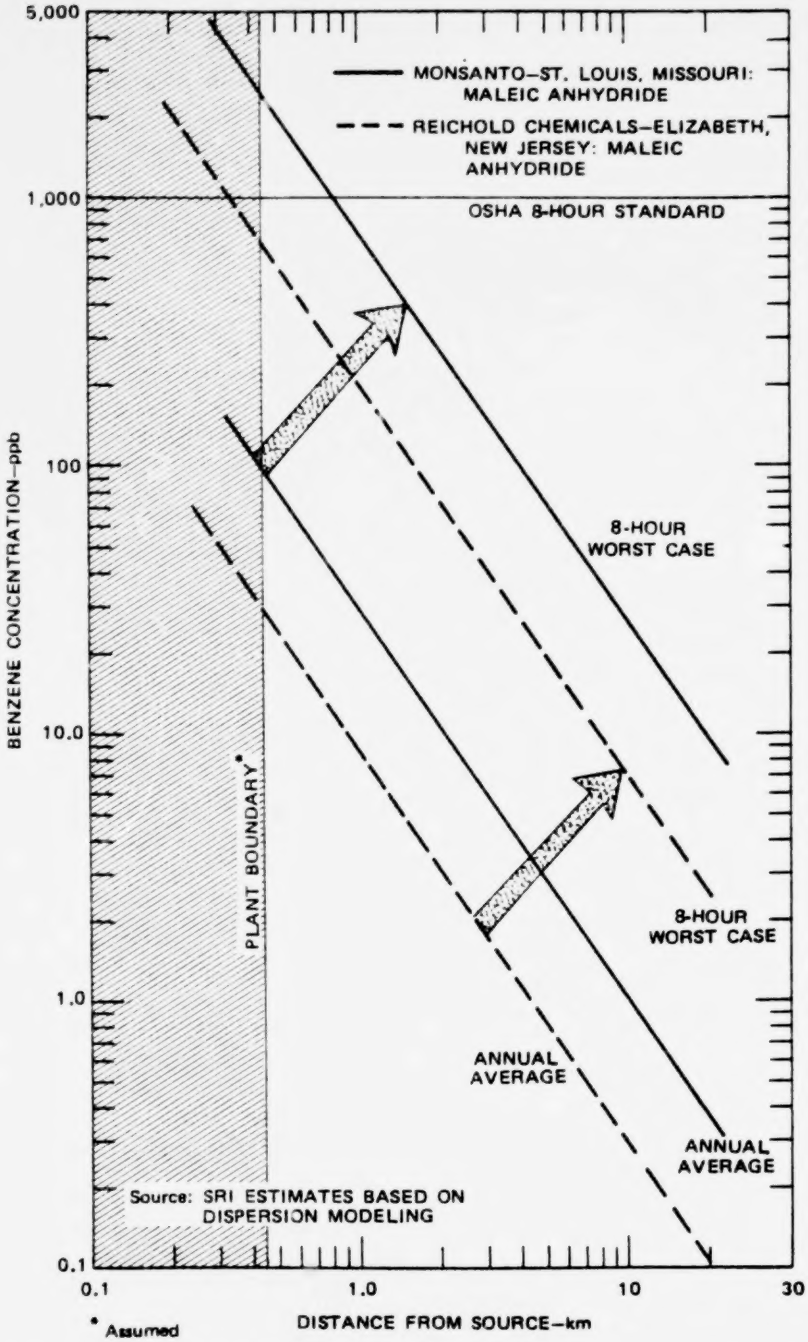


FIGURE III-4. COMPARISON BETWEEN PREDICTED ANNUAL AVERAGE AND 8-HOUR WORST CASE BENZENE CONCENTRATIONS IN THE VICINITY OF TWO CHEMICAL MANUFACTURING FACILITIES

peak concentrations would range from 41,000 to 12,000 ppb (41 to 12 ppm) at the plant boundary to 100 to 25 ppb 20 km from the source.

IV COKE OVENS

A. Sources

In 1975, 57.2 x 10^6 tons of coke were produced in the United States. The yield of coke from coal, averaging 68.4% in 1975, has remained fairly constant during the past decade (Sheridan, 1976). Coke is produced by 65 plants in the United States (Suta, 1977). The 65 plants, which are listed in Appendix C, consist of an estimated 231 coke-oven batteries containing 13,324 ovens. Their theoretical maximum annual productive capacity is 74.3 x 10^6 tons. Table IV-1 shows the estimated size and productive capacity in each state.

Coke ovens producing benzene as a by-product account for about 5 to 8% of the total benzene production in the United States. About 0.66% by volume benzene, 0.13% toluene, 0.05% xylene, and less than 0.10% of other aromatics have been identified in the coal gas generated from coking operations (Faith et al., 1966). The higher the temperatures in coking operations, the larger the amounts of aromatic hydrocarbons produced, particularly benzene. Reduction in quantities of paraffinic naphthenic (saturated alicyclic) and unsaturated hydrocarbons in the production is observed at high temperatures (Faith et al., 1966; McGannon, 1970). Carbonizing 1 ton of coal in coke ovens to produce blast furnace coke yields 3 to 4 gallons of light oil. The principal constituent of this oil is benzene, which comprises about 60 to 80% of the total composition. This crude light oil is then distilled to produce benzene, toluene, and xylene. The typical amount of benzene recovered from coke-oven gas is 1.85 gal/ton of coal carbonized (U.S. Public Health Service, 1970).

The distillation of coal tar is one additional source of benzene production. The amount of benzene produced varies with the coking and recovery processes and the grade of the raw coal. In general, the light

Table IV-1

ESTIMATED SIZE AND PRODUCTIVE CAPACITY OF BY-PRODUCT COKE PLANTS IN THE UNITED STATES ON DECEMBER 31, 1975

State	Number of Plants *	Number of Batteries	Number of Ovens	Maximum Annual Theoretical Productive Capacity (tons)	Coke Production in 1974 (tons)
Alabama	7	28	1,401	6,961,000	5,122,000
California	1	7	315	1,547,000	(1)
Colorado	1	4	206	1,261,000	(1)
Illinois	4	9	424	2,523,000	1,912,000
Indiana	6 (7)*	31	2,108	11,925,000	9,073,000
Kentucky	1	2	146	1,050,000	(1)
Maryland	1	12	758	3,857,000	(1)
Michigan	3	10	561	3,774,000	3,259,000
Minnesota	2	5	200	784,000	(1)
Missouri	1	3	93	257,000	(1)
New York	3	10	648	4,053,000	(1)
Ohio	12	35	1,795	9,960,000	8,842,000
Pennsylvania	12 (13)*	51	3,391	18,836,000	16,318,000
Tennessee	1	2	44	216,000	(1)
Texas	2	3	140	839,000	(1)
Utah	1	4	252	1,300,000	(1)
West Virginia	3 (4)*	13	742	4,878,000	3,555,000
Wisconsin	1	2	100	245,000	(1)
Undistributed	-	-	-	-	12,656,000
Total	62 (65)*	231	13,324	74,266,000	60,737,000

[1] Included in Undistributed.

* Colocated plants.

Source: Sheridan (1976).

oil distilled from coal tar is added to the major portion of light oil recovered from coal gas and refined for its benzene content. Appendix A contains a diagram of a typical coke-oven operation.

The basic coke-oven sources of air pollutant emissions include charging and topside emissions, emissions from doors during the coking cycle, waste gas stack emissions, pushing emissions, and quenching emissions. The only benzene concentration data available are occupational exposure data. Table IV-2 gives the typical benzene concentration ranges per occupation, within a coal-derived benzene recovery plant (NIOSH, 1974). Measurements of benzene in Czechoslovakia coke-oven plants are tabulated in Table IV-3. In the recovery plant, the benzene concentration can reach as high as 145 mg/m^3.

Table IV-2

AMBIENT LEVELS OF BENZENE WITHIN A COAL-DERIVED BENZENE PRODUCTION PLANT

Occupation	8-hour Time-Weighted Average (ppm)	Range (ppm)
Agitator operator	6.0	0.5 - 20
Benzene loader and loader helper	4.0	0.5 - 15
Benzene still operator	4.0	1 - 15
Light oil still operator	2.5	1 - 15
Naphthalene operator	10	2 - 30
Analyst	10	4 - 30
Chemical observer	10	4 - 50
Foreman	1.5	1 - 10

Source: Bethlehem Steel Corporation data (NIOSH, 1974).

Table IV-3

ATMOSPHERIC BENZENE EMISSION FROM THE COKING AND RECOVERY PLANTS IN CZECHOSLOVAKIA

Areas	Benzene Concentration $\mu g/m^3$
Coke-oven battery	$50. - 13 \times 10^3$
Recovery plant	$50. - 145 \times 10^3$
Tar processing	3×10^2

Source: Mašek (1971).

Data on benzene concentration in the vicinity of coke-oven and benzene recovery plants are unavailable. In coke-oven operations, the charging of coal is regarded as the potentially largest source of benzene emissions.

Many pollutants escape from coke-oven operations in addition to benzene. The major chemical compounds found in coke-oven emissions are identified in Table IV-4. The emissions consist of gases, condensable vapors, and particulate matter, many of which have documented toxic and/or carcinogenic properties. Therefore, the population exposed to coke-oven emissions of benzene is similarly exposed to many other chemical compounds.

B. Methodology and Exposures

To estimate the at-risk population to benzene from coke-oven emissions, the number of people residing around the coke-oven plants and the ambient benzene concentration must be determine. The general methodology discussed in Chapter III was used as the basis for determining exposure levels from coke ovens. Variations in geographic locations, meteorologic conditions and control technology were not considered in the analysis.

Table IV-4

PARTIAL LIST OF CONSTITUENTS OF COKE OVEN EMISSIONS

POLYNUCLEAR AROMATIC HYDROCARBONS

Anthanthrene[†]
Anthracene[†]
Benzindene[†]
Benz(a)anthracene[*]
Benz(b)fluoranthene[*]
Benzo(ghi)fluoranthene[*]
Benzo(j)fluoranthene[†]
Benzo(k)fluoranthene[†]
Benzofluorene[†]
Benzo(a)fluorene[†]
Benzo(b)fluorene[†]
Benzo(c)fluorene[†]
Benzophenanthrene[†]
Benzo(ghi)perylene[†]
Benzo(a)pyrene[*]
Benzo(e)pyrene[*]
Benzoquinoline[†]
Chrysene[*]
Coronene[†]
Dibenz(a,h)anthracene[*]
Dibenzo(a,h)pyrene[*]
Dihydroanthracene[†]
Dihydrobenzo(a)fluorene[†]
Dihydrobenzo(b)fluorene[†]
Dihydrobenzo(c)fluorene[†]
Dihydrobenz(a)anthracene[†]
Dihydrochrysene[†]
Dihydrofluoranthene[†]
Dihydrofluorene[†]
Dihydromethylbenz(a)anthracene[†]
Dihydromethylbenzo(k and b)fluoranthenes[†]
Dihydromethylbenzo(a and e)pyrenes[†]
Dihydromethylchrysene[†]
Dihydromethyltriphenylene[†]

Dihydrophenanthrene[†]
Dihydropyrene[†]
Dihydrotriphenylene[†]
Dimethylbenzo(b)fluoranthene[†]
Dimethylbenzo(k)fluoranthene[†]
Dimethylbenzo(a)pyrene[†]
Dimethylchrysene[†]
Dimethyltriphenylene[†]
Ethylanthracene[†]
Ethylphenanthrene[†]
Fluoranthene[†]
Fluorene[†]
Fluorene carbonitrile[‡]
Indeno(1,2,3-cd)pyrene[*]
Methylanthracene[†]
Methylbenz(a)anthracene[†]
Methylbenzo(a)pyrene[†]
Methylbenzo(ghi)perylene[†]
Methylchrysene[†]
Methylfluoranthene[†]
Methylfluorene[†]
Methylphenanthrene[†]
Methylpyrene[†]
Methyltriphenylene[†]
Naphthalene[‡]
Octahydroanthracene[†]
Octahydrofluoranthene[†]
Octahydrophenanthrene[†]
Octahydropyrene[†]
Perylene[†]
Phenanthrene[†]
O-Phenylenepyrene[†]
Pyrene[†]
Triphenylene[†]

POLYNUCLEAR AZA-HETEROCYCLIC COMPOUNDS

Acridine[†]
Benz(a)acridine[*]
Benzoquiniline[‡]

Dibenz(a,h)acridine[†]
Dibenz(a,j)acridine[†]
Isoquiniline[‡]
Quinoline[‡]

Table IV-4 (concluded)

AROMATIC AMINES

Aniline[‡]
β-Naphthylamine[*]
α-Naphthylamine[*]

OTHER AROMATIC COMPOUNDS

Benzene[*]
Mono-, di-, and tri-methylated pyridine[‡]
Phenol[§]
Pyridine[‡]
Toluene[**]
Xylene[**]

TRACE ELEMENTS

Arsenic[*]
Beryllium[*]
Cadmium[*]
Chromium[*]
Cobalt[*]
Iron[*]
Lead[*]
Nickel[*]
Selenium[*]

OTHER CASES

Ammonia[§]
Carbon disulfide[§]
Carbon monoxide[§]
Hydrogen cyanide[§]
Hydrogen sulfide[§]
Methane[§]
Nitric Oxide[**]
Sulfur dioxide[§]

MISCELLANEOUS ALIPHATIC COMPOUNDS

Acrolein[‡]
Aliphatic aldehydes[‡]
Formaldehyde[‡]
Methane[‡]

Key to sources: * Kornreich (1976)
† Lao, et al. (1975)
‡ Mabey (1977)
§ Smith (1971)
** White (1972)

Crude[*] dispersion modeling was conducted by Youngblood of EPA (1977c, 1978). Coke-oven operations usually cover a large area and benzene emissions are distributed widely throughout. Consequently, the point source model used by Youngblood to estimate downwind concentrations resulting from chemical manufacturing emissions is not applicable. To account for the emissions distributed over a large area, Youngblood used the PAL (Point, Area, and Line Source) Dispersion Model (Turner et al., 1975) that results in lower ambient impact for a given emission rate. The benzene emissions were assumed to occur primarily from oven leaks. The model assumptions were as follows: square plant area; uniform distribution of emissions throughout the area; effective stack height, 10 m; wind speed, 4 m/s; stability class, neutral (Pasquill Gifford "D"). Maximum, one-hour-average concentrations at selected downwind distances for a given emission rate of 100 g/s were obtained from PAL. These were divided by two to represent maximum eight-hour-averages. These are shown in Table IV-5.

The plant size most applicable to coke-oven operations is 0.25 km^2 (500 m on a side). The curve corresponding to this plant size is shown in Figure IV-1. An equation was developed through regression analysis to characterize this curve:

$$C = 403\ D^{-0.91} \tag{4.1}$$

where C is the 8-hour worst case benzene concentration in $\mu g/m^3$; and D is the distance from the source in km.

Equation (4.1) was then normalized to annual average conditions and to individual emission rates (the Youngblood model was based on an emission rate of 100 g/s):

$$C = 0.16\ E_a\ D^{-0.91} \tag{4.2}$$

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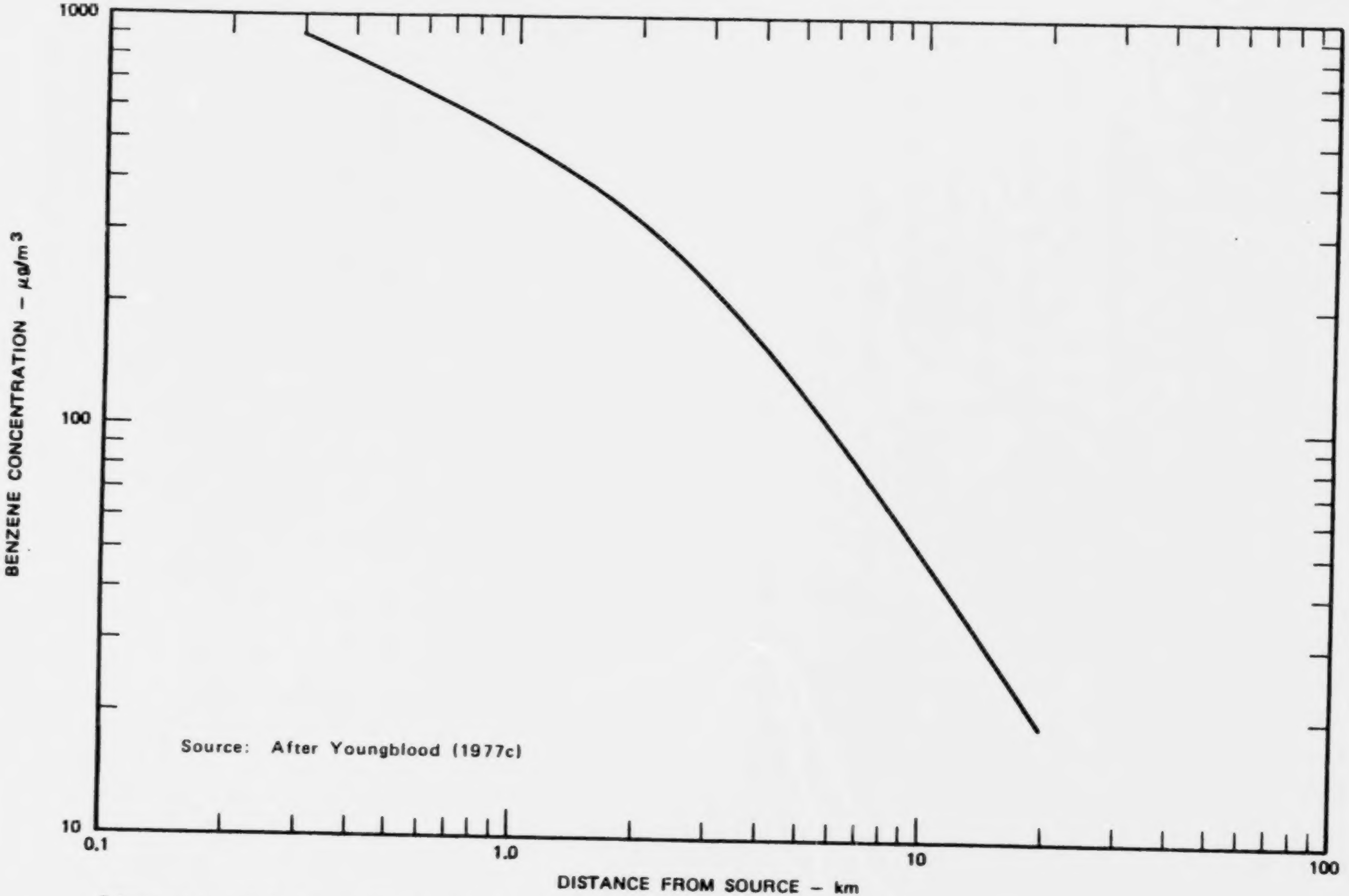
[*] In this report, "crude" is used to mean approximate and extrapolatable.



Source: After Youngblood (1977c)

* Based on an emission rate of 100 g/s. This is much higher than most coke-oven operations which usually have emission rates less than 10 g/s.

FIGURE IV-1. DISPERSION MODELING RESULTS FOR COKE-OVEN OPERATIONS*

Table IV-5

ROUGH ESTIMATES OF 8-HOUR WORST CASE BENZENE CONCENTRATIONS PER 100 g/s EMISSION RATE USING THE PAL DISPERSION MODEL

Distance From Source Area (km)	(Concentration $\mu g/m^3$)* for Given Plant Area						
	$0.01\ km^2$	$.06\ km^2$	$0.25\ km^2$	$1\ km^2$	$4\ km^2$	$9\ km^2$	$25\ km^2$
0.3	5,000	2,000	900	365	145	80	39
0.45	3,850	1,700	750	325	130	75	37
0.60	2,850	1,450	650	290	120	70	34
0.75	2,150	1,250	595	260	110	65	33
1.6	800	600	390	190	85	50	27
2.5	405	360	270	150	70	43	23
4.0	205	190	165	110	50	35	20
6.0	110	110	100	80	45	29	17
9.0	60	60	55	50	34	23	14
14.0	33	32	32	29	23	18	11
20.0	20	20	19	18	16	13	9

---

*To give rough estimates of annual average concentrations multiply by 0.04; to convert to ppb, divide concentrations by 3.2

Source: Youngblood (1977c).

To estimate the number of people exposed to benzene concentrations within each range at each location, Equation (4.2) is rearranged as follows to determine the distance at which the specified concentrations are found:

$$D_i = 0.133\left(\frac{E_a}{C_i}\right)^{1.10} \tag{4.3}$$

where C_i is the specified annual average concentrations (i.e., 0.1, 1.0, 4.0, and so on; input data, however, are in $\mu g/m^3$); D_i is the distance in km at which the specified concentration is found; and E_a is the emission rate in g/s at that location.

Detailed population estimates for as far as 15 km from each location were available from another SRI study (Suta, 1977). Consequently, once distances (D_i) were determined, the population exposed to benzene concentrations within each range was easily determined. Geographic coordinates for most of the coke plants were obtained from the U.S. EPA-NEDS data system. The remainder were obtained from consulting maps or by telephone conversation. The population residing within a 15-km radius about each coke plant was calculated by use of the Urban Decisions Systems, Inc., Area Scan Report. This computer data system contains the 1970 census data in the smallest area available (city blocks and census enumeration districts).

Emission rates for each coke-oven operation were estimated by basing them on the capacity and the emission factor of 0.06 lb benzene/ton of coal* obtained from EPA document AP-42 (EPA, 1976). Because actual production data are unobtainable, capacity production and 24-hour (365 days) operation were assumed. Appendix C lists the estimated emission rates Three plants were colocated and their corresponding emission rates were summed. The emissions of benzene from the coke plants were assumed to be the sole contributors of benzene to the atmosphere in the vicinity of the oven.

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*Estimated by multiplying the hydrocarbon emission factor (4.2 lb/ton of coal) by the fraction of benzene in the total hydrocarbon emissions (0.0132).

Table IV-6 summarizes people exposed to various annual average benzene concentrations by state. Approximately 300,000 people are exposed to annual average concentrations greater than 0.1 ppb (8-hour worst case concentration greater than 2.5 ppb). Pennsylvania has the highest number of exposed population (43% of the total), followed by Indiana (19%) and Michigan (12%).

Table IV-6

ESTIMATED POPULATION EXPOSED TO BENZENE FROM COKE OVENS, BY STATE

State	Population Exposed[*] to Benzene (ppb)[†] 0.1 - 1.0
Alabama	8,700
California	1,400
Colorado	-
Illinois	830
Indiana	58,000
Kentucky	550
Maryland	19,000
Michigan	36,000
Minnesota	-
Missouri	-
New York	24,000
Ohio	17,000
Pennsylvania	130,000
Tennessee	-
Texas	-
Utah	20
West Virginia	3
Wisconsin	-
Total[‡]	300,000

---

[*] Totals for each state are rounded to two significant figures; a dash (-) indicates that no exposed population was estimated by our method for the annual average concentrations listed. There may be some population exposed to those concentrations for shorter periods of time.

[†] Annual average concentrations; to convert to 8-hour worst case, multiply by 25; to convert to $\mu g/m^3$, multiply by 3.2.

[‡] Total is rounded to one significant figure.

Source: SRI estimates.

V PETROLEUM REFINERIES

A. Sources

Petroleum refineries appear to be a significant source of atmospheric benzene emissions, with more than 250 operating in 39 states. Benzene is a constituent in crude oil and gasoline, and is produced as a by-product of the refining process. Benzene emissions from a refinery include: (1) process emissions from light and heavy naphtha streams from the crude unit; fluid catalytic cracking units; hydrocracking units; gasoline treating units, and pumps, flanges, and other sources of fugitive emissions; and (2) nonprocess emissions from wastewater treatment facilities, heaters and boilers, and facilities for storage and handling of benzene and gasoline (PEDCO., 1977).

Benzene produced from catalytic reforming extraction by petroleum refineries accounted for 50% of the benzene supply in the United States in 1976 (SRI estimates). Because the average distribution of aromatics in reformate is 10% benzene, 40% toluene, and 50% xylene, toluene dealkylation processes are being used more frequently to increase the benzene fraction. (Faith et al., 1966). Toluene dealkylation to produce benzene currently accounts for 27% of the benzene supply in the United States (SRI estimates). This process is most common in petrochemical complexes, rather than in the petroleum refineries. Table V-1 lists the petroleum refineries in each state that extracts aromatics from the reformate produced in catalytic reforming. Texas and Louisana account for 84% of the total production of benzene, toluene, and xylene.

The composition of crude oil varies widely, but commonly contains about 0.15% benzene by volume (Dickerman et al., 1975). Consequently, benzene is emitted during the refining process. We have assumed that refineries with catalytic reforming of benzene (34 out of 266 refineries) have larger benzene emissions than those without catalytic reforming because of the processing and handling involved. Many of the refineries with catalytic reforming of benzene use it captively in the production of a wide variety of chemicals; others sell some or all of the benzene produced to chemical manufacturers.

Table V-1

PETROLEUM REFINERIES PRODUCING AROMATICS,* BY STATE

State	Number of Plants	Quantity* (bbl/stream day)
California	3	5,990
Illinois	2	6,700
Kansas	1	1,400
Kentucky	1	4,000
Louisiana	3	19,100
Mississippi	1	6,000
New York	1	3,000
Oklahoma	1	2,000
Pennsylvania	3	9,700
Texas	18	122,525
Total	34	180,415

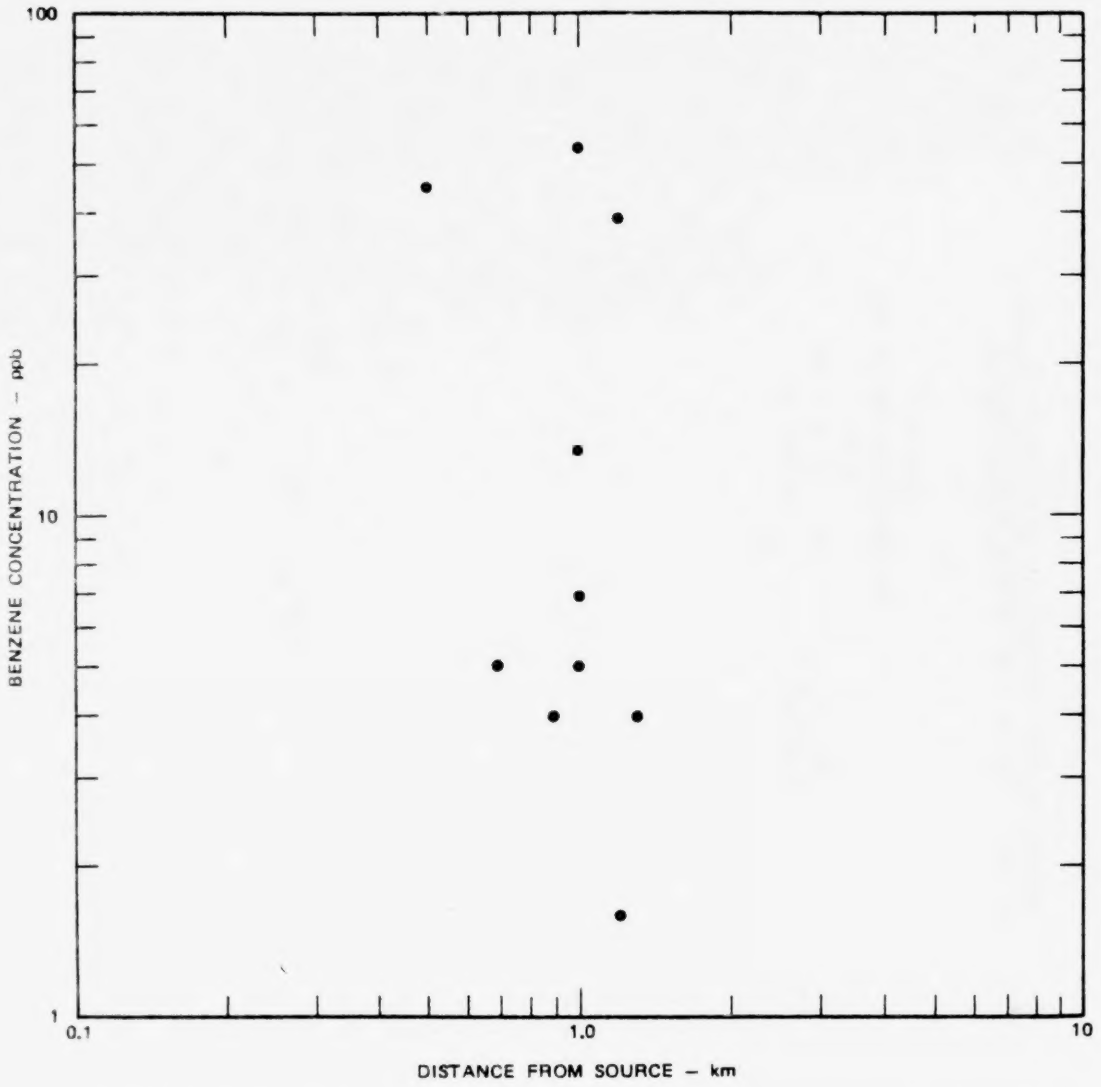
---

*Total quantity of benzene, toluene, and xylene produced.

Source: Oil & Gas Journal (May 28, 1977)

Monitoring data from one refinery producing benzene as a by-product are shown in Figure V-1. Even though all samples were collected during the same day, the measurements varied widely. Furthermore, the limited nature of these data makes extrapolation unreliable.

The American Petroleum Institute (API) conducted atmospheric monitoring for benzene in the vicinity of petroleum refineries in summer 1977 (draft report, 1977, cited in PEDCo, 1978). Four refineries in different geographic locations were sampled for 24 hours. Quality



[*] Collected in activated charcoal tubes and analyzed by gas chromatograph with a flame ionization detector. Detection limit was approximately 0.1 μg of benzene/100 mg charcoal.

Source: EPA, 1977

FIGURE V-1. MONITORING DATA[*] FOR GULF ALLIANCE REFINERY, BELLE CHASSE, LOUISIANA

Table V-2

ATMOSPHERIC BENZENE CONCENTRATIONS AT DISTANCES GREATER THAN 1 KM FROM PERIMETER OF PETROLEUM REFINERIES

Geographic Location of Refinery	No. of Samples*	Average Benzene Concentration (ppb) at > 1 km from Perimeter
Mid-Atlantic	3	3
Pacific Northwest	1	2
Midwest	7	< 1
Gulf Coast	3	5

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*24-hour samples.

Source: API (1977), as cited in PEDCo (1978).

control information is unavailable for these measurements. Concentrations beyond 1 km from the plant perimeter ranged from less than 1 ppb at one location to 5 ppb at another. Table V-2 summarizes this information.

Radian Corporation conducted atmospheric benzene monitoring for Shell Oil Company in the vicinity of the Shell Oil petrochemical refinery in Deer Park, Texas, for 6 consecutive days in December, 1977 (Radian, 1978). Under varying meteorological conditions, the sample site 400 m from the plant perimeter showed 24-hour concentrations ranging from 2 to 13 ppb, with a 6-day average of 7 ppb. Complete quality control information is unavailable for these data.

At the request of EPA, Research Triangle Institute reanalyzed the results of previously collected ambient monitoring data stored on computer tape to determine benzene concentrations (Research Triangle Institute, 1977). Table V-3 indicates the results for eleven samples collected in the vicinity of petroleum refineries. All sampling occurred within or near the plant perimeter except for the St. Louis sample which was taken 3.2 km (2 miles) east of the Shell refinery.

Table V-3

RESULTS OF AMBIENT BENZENE MONITORING
IN THE VICINITY OF PETROLEUM REFINERIES

Location	Facility	Number of Samples	Average Benzene Concentration (ppb)
Deer Park, Pasadena, TX	Shell, Tenneco	9	3.4
El Segundo, CA	Chevron	1	258
St. Louis, MO	Shell	1	72

Source: Research Triangle Institute, 1977.

The results of atmospheric monitoring in the vicinity of petroleum refineries give widely differing estimates of ambient benzene concentrations. Differences in analytical techniques, sampling periods, meteorologic conditions, and plant operations probably affected the estimated concentrations significantly.

Four states have 60% of the refining capacity in the United States: California (14%), Illinois (7%), Louisiana (13%), and Texas (26%). Pennsylvania (5%) and New Jersey (4%) bring the total to 69%. Thus, 15% of the states (6 out of 39 states) with petroleum refineries account for 69% of the refining capacity.

B. Methodology

1. Refining of Crude Oil

The general methodology discussed in Chapter III was used as the basis for determining exposure levels from petroleum refineries. Youngblood of EPA conducted dispersion modeling (1977c, 1978) to characterize benzene emissions from petroleum refineries. The results were then applied to each refinery by computer program to estimate the exposed population. Emissions are highly variable, depending on the size and age of the plant and on the control technology employed; however, because specific emission factors were unavailable, general averages were used. Because actual production data are unobtainable, capacity production and 24-hour (365 days) operation were assumed. Variations in geographic location and meteorological conditions were not considered.

Estimates of refinery emission factors were based on average hydrocarbon emissions and the percent of the total hydrocarbon emissions attributed to benzene. Evaluations of available information and discussions with EPA (Radian Corporation, 1975; Hustvedt, personal communication, June 1977a) resulted in the selection of the following factors:

- Total hydrocarbon emissions from petroleum refineries = 920 lb/1,000 bbl
- Estimated percentage of hydrocarbon emissions attributed to benzene from refineries without catalytic reforming = 0.5

- Estimated percentage of hydrocarbon emission attributed to benzene from refineries with catalytic reforming = 1.0.

These emissions result from gasoline storage losses (≈50%) and from leaks and stacks (≈50%). Table V-4 presents the calculations of emission factors from the two types of petroleum refineries identified. The listing of U.S. petroleum refineries, shown in Appendix D, was obtained from the Annual Refining Survey published in the Oil & Gas Journal (March 28, 1977). This listing includes a breakdown of refineries that extract benzene, toluene and xylene from the reformate as well as the plant capacities. The emission rate in g/s for each plant was estimated, based on the plant capacity and the emission factor. The emission rate for each plant is shown in Appendix D.

Table V-4

CALCULATION OF EMISSION FACTORS FOR PETROLEUM REFINERIES

Refineries with catalytic reforming:

$$\frac{0.92\ \text{lb/bbl}\left(\begin{matrix}\text{total hydro-}\\ \text{carbon emissions}\end{matrix}\right) \times 0.01 \left(\begin{matrix}\text{percent}\\ \text{benzene}\end{matrix}\right) \times 10^3\ \text{g/kg}}{0.159\ \text{m}^3/\text{bbl} \times 2.2\ \text{lb/kg}} = 26\ \text{g/m}^3$$

Refineries without catalytic reforming:

$$\frac{0.92\ \text{lb/bbl}\left(\begin{matrix}\text{total hydro-}\\ \text{carbon emissions}\end{matrix}\right) \times 0.005 \left(\begin{matrix}\text{percent}\\ \text{benzene}\end{matrix}\right) \times 10^3\ \text{g/kg}}{0.159\ \text{m}^3/\text{bbl} \times 2.2\ \text{lb/kg}} = 13\ \text{g/m}^3$$

Because petroleum refineries are large and benzene emissions are distributed widely throughout the plant area, Youngblood used the PAL (Point, Area, Line Source) Dispersion Model (Turner et al.) to estimate approximate downwind concentrations. The modeling assumptions and procedure were the same as those described for coke ovens (Chapter IV). Table IV-6 applies to petroleum refineries as well as to coking plants.

Three of the size categories are applicable to petroleum refineries (Hustvedt, personal communication, 1977b):

Plant Area (km^2)	Capacity (bbl/day)
0.25	< 35,000
1.00	35,000 - 200,000
4.00	>200,000

Figure V-2 shows the curves corresponding to the three plant sizes. Because the differences between the curves are within the range of uncertainty associated with dispersion analysis, the middle curve (1.0 km^2) was used to represent the dispersion characteristics of all refineries at the suggestion of Youngblood (personal communication, August 1977).

The computer program discussed in Chapter III was applied to petroleum refineries by substituting a new equation developed through regression analysis to characterize the 1.0-km^2 curve. This equation can be written as follows:

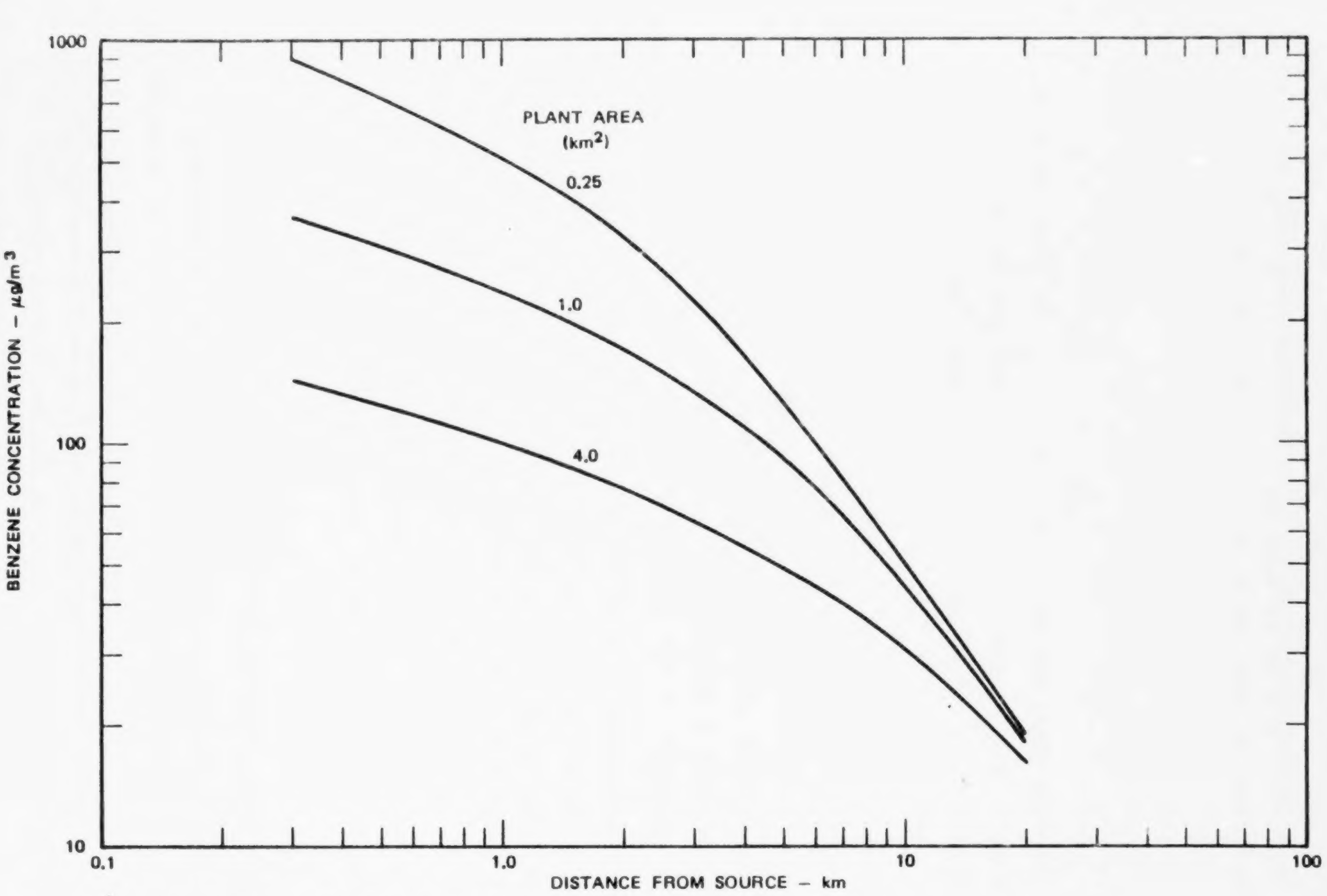
$$C = 200\ D^{-0.51} \tag{5.1}$$

where, C is the 8-hour worst-case benzene concentration in $\mu g/m^3$; and D is the distance from the source in km.

Equation (5.1) was then normalized to annual average conditions and individual emission rates (the Youngblood model was based on an emission rate of 100 g/s):

$$C = 0.08\ E_a D^{-0.51} \tag{5.2}$$

where, E_a is the emission rate in g/s for the location of interest.



* Based on an emission rate of 100 g/s. This is much higher than most petroleum refineries which usually have emission rates less than 10 g/s.

Source: After Youngblood (1977c)

FIGURE V-2. DISPERSION MODELING RESULTS FOR THREE SIZE CATEGORIES OF PETROLEUM REFINERIES*

To estimate the people exposed to benzene concentrations within each range at each location, Equation (5.2) is rearranged as follows to determine the distance at which the specified concentrations are found:

$$D_i = 0.007 \left(\frac{E_a}{C_i} \right)^{1.96} \qquad (5.3)$$

where, C_i is the specified concentration (i.e., 0.1, 1.0, 4.0, and so on; input data, however are in $\mu g/m^3$); and D_i is the distance in km at which the specified concentration is found. The remaining steps in the methodology are discussed in Chapter III.

If more than one refinery was located in a particular city, we assumed that the refineries were co-located, and we summed their emission rates. Although several cities had three or more refineries, it is also true that few people generally live near such complexes. Thus, with this method, the exposed population is minimized, whereas the exposure level is maximized for a particular city.

For locations with fewer than three refineries, an area of 0.8 km^2 (circle with a radius of 500 m) was assumed to be within the plant boundary. No exposed population was estimated within this area. For locations with three or more refineries, an area of 1.0 km^2 (circle with a radius of 600 m) was assumed to be within plant boundaries.

Benzene emissions from petroleum refineries were assumed to be the sole contributors of benzene to the atmosphere in the vicinity of the refinery.

2. Storage and Transfer of Pure Benzene

Benzene is produced as a salable by-product by 36 petroleum refineries. The benzene emission rates associated with storing, handling, and distributing pure benzene are much higher than those associated with storing, handling, and distributing gasoline. Because the calculation of emission rates for petroleum refineries did not include emissions from storage and transfer of pure benzene, the additional benzene emissions were calculated for the 36 refineries and added to the emission rates calculated in the previous section. A discussion of the methodology and assumptions used follows.

The emission factors for storage and transfer of pure benzene are shown in Table V-5. Information on the type of storage and transfer operation in use at 12 refineries was made available in summary form by the Chemical and Petroleum branch of EPA's Office of Air Quality Planning and Standards from the Section 114 letter sent out in 1977 (Brothers, personal communication, 1978). That information was used along with the following assumptions in determining the benzene emission rate at each refinery:

Table V-5

SUMMARY OF EMISSION FACTORS FOR PURE BENZENE STORAGE AND TRANSFER

Facility	Control Type	Benzene Emission Factor (g/gal)	Reference*
Benzene storage	Uncontrolled	3.0	1
Benzene storage	Internal floating roof, vapor recovery	0.3	2
Benzene transfer			
Inland barge	Uncontrolled	0.76	3
Tank truck	Uncontrolled	1.8	1
Rail car	Uncontrolled	1.8	1

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*Key to references:
1. Durham, personal communication, 1978.
2. Burr, personal communication, 1978.
3. Markwordt, personal communication, 1978.

- Benzene production is about 82% of capacity (SRI estimates).
- If all of the benzene produced was used captively, only storage emissions were assumed.
- If some portion of the benzene produced was known to be used captively, loading emissions were only attributed to the percentage sold to outside customers.
- If no information was available concerning the type of benzene transfer operation at a refinery, tank trucks and/or rail cars were assumed for all benzene transfers. If information was available, percentages of the total production were assigned to barge or rail/truck transfer, and the associated emission was determined.
- If no information was available concerning the type of storage at a particular refinery, uncontrolled storage was assumed.
- The average benzene storage tank was assumed to hold 55,000 barrels (Durham, personal communication, 1978). Every tank was assumed to have a 26-day retention time (Burr, personal communication, 1978).

Truck and rail loading of benzene takes place in a centralized location that is at a distance from the storage tanks. Barges and tankers are loaded at another location. Therefore, emissions from loading operations derive from one or two locations distinct from the storage tank area. Because storage and transfer emissions are distributed over a large area, they are considered to be area-wide emissions and can thus be added to the refinery emission rate calculated in the previous section. Equation (5.3) is then applied to determine the exposed population. Table D-1 in Appendix D lists each petroleum refinery and the estimated emission rates.

C. Exposures

The population exposed to atmospheric benzene from petroleum refineries by plant location is shown in Appendix D. A state summary of annual average concentrations and exposed population is shown in Table V-6. More than 5 million people are exposed to benzene from petroleum refineries. Virtually all of the estimated population is exposed to annual average concentrations between 0.1 and 1.0 ppb. In only two

Table V-6

ESTIMATED POPULATION EXPOSED TO BENZENE FROM PETROLEUM REFINERIES, BY STATE

State	Population Exposed[*] 0.1-1.0 (ppb)[†]	Population Exposed[*] 1.1-4.0 (ppb)[†]
Alabama	-	
Alaska	-	
Arizona	-	
Arkansas	-	
California	230,000	
Colorado	-	
Delaware	100	
Florida	-	
Georgia	-	
Hawaii	-	
Illinois	110,000	
Indiana	4,300	
Kansas	280	
Kentucky	6,000	
Louisiana	240,000	
Maryland	-	
Michigan	6,000	
Minnesota	10	
Mississippi	30,000	
Missouri	-	
Montana	-	
Nebraska	-	
New Hampshire	-	
New Jersey	51,000	
New Mexico	-	
New York	20,000	
North Dakota	-	
Ohio	300,000	
Oklahoma	8,100	
Oregon	-	
Pennsylvania	2,000,000	
Tennessee	-	
Texas	1,500,000	2,600
Utah	-	
Virginia	-	
Washington	80	
West Virginia	-	
Wisconsin	-	
Wyoming	-	
Total[‡]	5,000,000	3,000

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[*] Totals for each state are rounded to two significant figures; a dash (-) indicates that no exposed population was estimated by our method for the annual average concentrations listed. There may be some population exposed to those concentrations for shorter periods of time.

[†] Annual average concentrations; to convert to 8-hour worst case, multiply by 25; to convert to $\mu g/m^3$, multiply by 3.2.

[‡] Totals are rounded to one significant figure.

Source: SRI estimates.

locations, Port Arthur and Corpus Christi, Texas, are people exposed to annual average concentrations higher than 1.0 ppb. Pennsylvania, which is fifth in number of petroleum refineries, has the highest exposed population with 2,000,000; Texas is second with 1,500,000. Five states account for almost 90% of the total population exposed to benzene from petroleum refining.

VI SOLVENT OPERATIONS

A. Sources

Little is known about benzene used in solvent operations. Recent publications evaluating benzene in the workplace have identified industries in which benzene may be used as a solvent, but the studies were unable to quantify actual volumes of use (Arthur D. Little, Inc., 1977; PEDCo, 1977; Mitre, 1976). The Occupational Safety and Health Administration (OSHA) is currently evaluating industries for benzene hazards under their newly promulgated standards. In addition, a detailed study of market input and output of benzene in solvent operations is currently being conducted for the Office of Toxic Substances. Table VI-1 lists major industries that OSHA is investigating to determine whether benzene is used as a solvent in their operations.

Some indication of the maximum possible volume of benzene used in solvent operations can be obtained by evaluating benzene consumption data for the United States. More than 95% of all benzene used as a raw material is consumed by seven chemical manufacturing processes (see Chapter III). Only 2.8% (3.05×10^8 lb [1.39×10^8 kg]) is consumed by other uses (SRI estimates, 1977). Other uses include benzene for: anthraquinone, benzene hexachloride, benzene sulfonic acid (primarily for phenol), diphenyl, hydroquinine, nitrobenzene (other than that used for aniline), resorcinol, and solvent applications. Because three of the uses (resorcinol, nitrobenzene, and benzene sulfonic acid) account for approximately 50% of the benzene consumed by all other uses, solvent operations must consume much less than 150×10^6 lb/yr (68.0×10^6 kg). In fact, many operations have switched to other solvents because of the toxicity hazard associated with benzene. The amount of benzene used by solvent operations is consumed in many, small volume markets (SRI estimates, 1977).

Table VI-1

INDUSTRIES AND MANUFACTURED PRODUCTS POSSIBLY USING BENZENE AS A SOLVENT

- Rubber tires
- Miscellaneous rubber products
- Adhesives
- Gravure printing inks
- Printing and publishing
- Trade and industrial paints
- Paint removers
- Miscellaneous industrial uses
- Coated fabrics
- Synthetic rubber
- Leather and leather products
- Floor covering

Source: Brinkerhoff, personal communication, 1977.

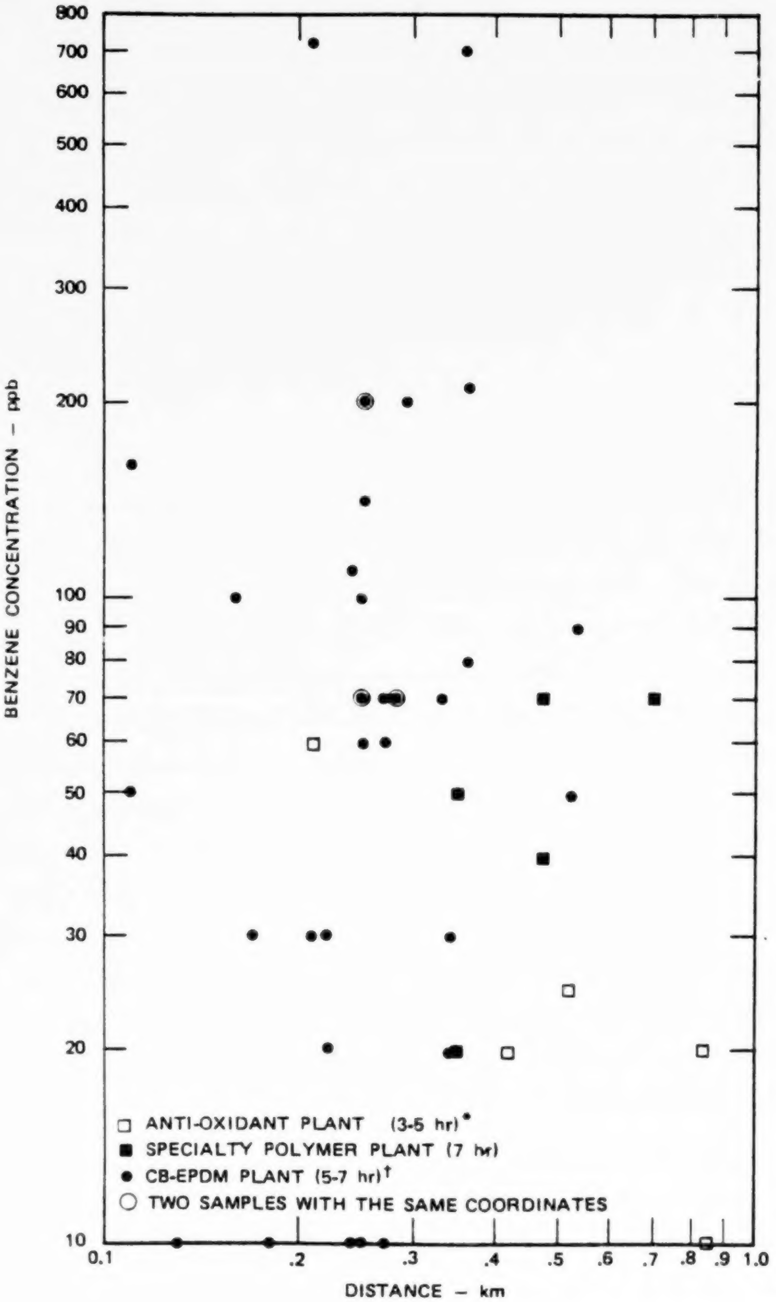
A recent study by Arthur D. Little (ADL) (1977a) identified the manufacture of rubber tires and of miscellaneous rubber products using synthetic rubber and adhesives as possible major sources of occupational exposures. Although industry sources indicate that benzene has been removed from many of the operations within the rubber industry, the ADL study reported that substantial quantities are still being used in the manufacture of synthetic rubbers, production of phenolic antioxidants, polymerization of hydrophilic polymers, and manufacture of rubber adhesives. However, these operations may take place in locations apart from the location where the final product is produced.

Limited monitoring data are available. NIOSH is currently conducting a sampling program in the vicinity of solvent operations using benzene (Hardel, personal communication, 1977). Sampling data for three B.F. Goodrich Chemical Company solvent operations were recently submitted to EPA. Figure VI-1 displays the measured benzene concentrations at various sampling sites within 1 km of the source. Benzene concentrations were highly variable, ranging from nondetectable to 720 ppb. (The wide variability probably occurred because the wind was gusty, averaging between 10 and 15 mph throughout the sampling period.) Complete quality control information is unavailable for these data. The potential for environmental exposure to benzene from solvent operations appears to be significant.

B. Methodology and Exposure

Because of the extremely limited information on operations using benzene as a solvent, amount used, and probable emission factors, any exposure estimates are necessarily crude. The primary assumption is that only the largest plants will have significant potential for high environmental exposure. The 1972 Census of Manufacturers (Bureau of the Census) was used to determine those operations that have the largest average plant size. Table VI-2 lists the major operations and average number of employees per plant. Five operations that averaged more than 100 employees per plant were selected for further analysis. Table VI-3 lists the number of plants and average number of employees per plant for each of the five operations by state. Georgia and California have the largest number of plants, together comprising 32% of the total. Based on Table VI-3, it can be assumed that the population in the states with the most plants has the greatest risk of benzene exposure from the solvent operations identified.

The approximate benzene used for each operation can be roughly estimated by assuming average plant sizes. As discussed in the previous section, it is known that 150×10^6 lb/yr of benzene (68×10^6 kg/yr) is used for other unidentified uses and that solvent applications represent less than half of that figure. If it is assumed that 40% of this figure represents solvent use, the total is 60×10^6 lb/yr (27×10^6 kg/yr). Because it is expected that the largest single solvent application is in rubber tires and miscellaneous rubber products, it is further assumed that 80% of the total estimated solvent use is found in



* The hours shown in parenthesis are approximate averaging times for the samples taken at each plant

† Points plotted by B. F. Goodrich Personnel (Kilroy, personal communication, 1978)

FIGURE VI-1. SAMPLING DATA FOR THREE SOLVENT OPERATIONS

Table VI-2

AVERAGE NUMBER OF EMPLOYEES PER PLANT FOR SELECTED SOLVENT OPERATIONS

SIC Number	Item	Average Number of Employees/Plant
221	Floor covering mills	113
229	Miscellaneous textile goods	60
278	Blankbooks and bookbinding	35
282	Plastics materials, synthetics	351
285	Paints and allied products	41
301	Tires and innertubes	522
302	Rubber and plastics footwear	295
303	Reclaimed rubber	45
304	Rubber, plastic hose, and belting	354
306	Fabricated rubber products	89
307	Miscellaneous plastic products	45
31	Leather and leather products	84
379	Miscellaneous transportation equipment	38

Source: adapted from 1972 Census of Manufacturers.

Table VI-3

NUMBER OF PLANTS AND EMPLOYEES FOR SOLVENT OPERATION WITH HIGH POTENTIAL FOR BENZENE EMISSIONS

	Tires and Innertubes		Rubber, Plastic Hose and Belting		Rubber and Plastic Footware		Plastics Materials, Synthetics		Floor Covering Mills		Number of Plants
	#	E	#	E	#	E	#	E	#	E	
Alabama	10	800					9	400	7	300	26
Arkansas	5	400	1	300	1	300			5	150	12
California	22	500*	8	750	3	100	51	40	62	100*	146
Colorado	2	900	1	350	1	300					4
Connecticut	1	1800	2	100	3	1200	9	200			15
Delaware			2	900			6	700			8
Florida					4	450	10	580			1-
Georgia	9	200			3	600	11	100	247	100	270
Illinois	10	500*	4	400	2	375	27	100	7	100	50
Indiana	5	360	3	100	3	250	9	160	2	100	22
Iowa	5	700					3	100			8
Kansas	2	1750	1	200			3	100			6
Kentucky	3	600	1	750			10	450	3	100	17
Louisiana							14	264			14
Maine					5	360					5
Maryland	2	1750			3	1200	5	580			10
Massachusetts	6	600	4	450	12	300	21	200	10	100	53
Michigan	6	600					13	300			19
Minnesota			2	100			4	200			6
Mississippi	3	600					5	150	1	1800	9
Missouri	4	100	2	600	4	100	4	50			14
Nebraska			3	600							3
New Hampshire					7	250	3	70	2	150	12
New Jersey			18	350*	5	150	35	150	3	100	61
New York			5	360	10	180	20	100	17	20	52
North Carolina	7	400	2	900	4	450	22	700			35
North Dakota									38	100	38
Ohio	27	1000	15	600	6	50	37	200			85
Oklahoma	7	600	1	300					6	200	14
Pennsylvania	14	500*	4	200	9	250	27	400	27	200	81
Rhode Island					2	900			8	25	10
South Carolina			1	300	1	200	15	1100	30	100	47
Tennessee	12	460	1	750	5	150	15	1400	20	80	53
Texas	11	500*					35	280	4	100	50
Utah			2	150							2
Virginia	5	360			1	200	10	1800	3	600	19
West Virginia					2	150	6	1200			8
Wisconsin	2	1750			1	750	10	100			13
Total	180		83		97		502		449		1311

- Number of plants

E - Average number of employees per plant

* - The average plant size for the category. This was used when it was not possible to determine an average plant size for the State from the listed information.

Source: 1972 Census of Manufacturers, Bureau of the Census; 1975 Statistical Abstract of the United States, Bureau of the Census.

rubber-related manufacturing. Therefore, the amount allocated to rubber tires and miscellaneous rubber products is estimated to 48 x 10^6 lb/yr (22 x 10^6 kg/yr). Table VI-3 shows 360 plants in rubber-related manufacturing. Using this total, the average benzene consumption per plant is estimated at 0.13 x 10^6 lb/yr (0.06 x 10^6 kg/yr).

Estimating the level of risk associated with each plant is difficult. In most operations, nearly 100% of the quantity used as a solvent is emitted to air or water. Because benzene is highly volatile, it is likely that most of the solvent is emitted to the atmosphere. If all solvent were emitted to the air, an average plant in rubber-related manufacturing would have an emission rate of 2 g/s if uniform solvent use over a 24-hour, 365-day work year is assumed. The resulting benzene concentrations would range from approximately 7 ppb at the plant perimeter to 0.1 ppb at 20 km (if an area-wide emission within a 0.06 km^2 area is assumed: see Table IV-5). Although more exact estimates are impossible, given the available information, the potential for environmental exposures appears to be significant.

The states containing the most plants with high potential for atmospheric benzene emissions are identified in Table VI-4. It is impossible to discern with certainty whether or not benzene is actually used at these facilities. The probability of benzene use is high, however, and, if used, the probability of annual average benzene concentrations of 0.1 ppb or greater is significant. In fact, all the plants identified in Table VI-4 are at least two times larger than the average plant size in their category (based on total number of employees).

This same methodology can be used to determine potential emissions in the remaining two categories: plastics materials, synthetics, and floor covering mills. If it can be assumed that they account for 15% of benzene consumed for solvents, the total use for these two manufacturing processes is estimated to be 9.0 x 10^6 lb/yr (4 x 10^6 kg/yr). With 951 plants, the average benzene consumption is 9 x 10^3 lb/yr (4 x 10^3 kg/yr) per plant. The emission rate calculated for an average plant is 0.1 g/s, or more than 1 order of magnitude lower than that for

Table VI-4

STATES WITH THE HIGHEST POTENTIAL FOR ATMOSPHERIC BENZENE FROM SOLVENT OPERATIONS

State	Number of Plants	Average Number of Employees Per Plant	Average State Density (1974) (People/km^2)	Plant Size as Compared to Estimated Average Plant*
Tires and innertubes				
Connecticut	1	1,800	244	3x
Kansas	2	1,750	11	3x
Maryland	2	1,750	159	3x
Ohio	27	1,000	101	2x
Wisconsin	2	1,750	32	3x
Rubber, plastic hose, and belting				
California	8	750	52	2x
Delaware	2	900	111	2.5x
Kentucky	1	750	33	2x
North Carolina	2	900	42	2.5x
Tennessee	1	750	38	2x
Rubber and plastics footwear				
Connecticut	3	1,200	244	4x
Georgia	3	600	32	2x
Rhode Island	2	900	343	3x
Wisconsin	1	750	32	2.5x

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*See text for discussion of the estimated average plant size.

Source: 1972 Census of Manufacturing and 1975 Statistical Abstract of the United States (Bureau of Census).

rubber-related manufacturing. Thus, if the estimated percentage of benzene use attributed to the rubber industry versus other solvent uses is correct, the exposures related to other solvent operations are minimal. As noted earlier, use of benzene as a solvent in operations other than the rubber industry is generally declining. Although it is also declining in the rubber industry, the use volume is still presumed to be high (ADL, 1977a).

In summary, although little is known about the use of benzene as a solvent, present indications are that its use for this purpose is declining. Crude estimates of emissions and available monitoring data indicate that there is a potential for environmental exposures as long as benzene is used as a solvent. Available monitoring data indicate that the levels could be high in the vicinity of some facilities. Rubber-related manufacturing is estimated to be the largest source of population exposures in this category, although estimating the population exposed was impossible from the information available. Consequently, further study of solvent operations including volumes of benzene, ventilation practices, and characterization of emissions is warranted. It is likely that environmental exposures will increase because OSHA regulations will require reduced occupational exposures.

VII STORAGE AND DISTRIBUTION OF GASOLINE

A. Sources

Storage and distribution of gasoline represent potential sources of atmospheric benzene in the environment. There are two main emission pathways: (1) evaporation and spills during loading and unloading and (2) spills from collisions in transportation.

Gasoline transfers normally occur at petroleum refineries and at numerous storage sites throughout the United States. Gasoline is usually stored in closed containers located in remote locations. Although evaporation loss from storage tanks has been observed, most of the benzene released into the environment is believed to result from the operations of loading and unloading the gasoline. Spills from collisions involving gasoline transfer vehicles account for negligible benzene losses. The gasoline marketing distribution system is shown in Figure VII-1.

1. Storage

Storage facilities consist of closed storage vessels, including pressure, fixed-roof, floating-roof, and conservation tanks. Ordinary fixed-roof tanks store less volatile petroleum products, whereas floating-roof tanks are most commonly used to store gasoline. Diagrams of several of these tanks are shown in Appendix A. Emissions of benzene from storage in a floating-roof tank occur primarily from standing and withdrawal (wetting) losses. Fixed-roof tanks have "breathing" losses caused by expansion and contraction of the vapors due to diurnal changes in atmospheric temperature. Because of the low volume of gasoline stored in fixed-roof tanks, breathing losses are not considered to be a significant source of atmospheric benzene.

Limited data have been reported on benzene exposures adjacent to storage facilities. A survey of industry reported an average of 375 ppm of benzene measured next to the sampling port on top of a benzene storage tank (Young, 1976, cited in PEDCo, 1977).

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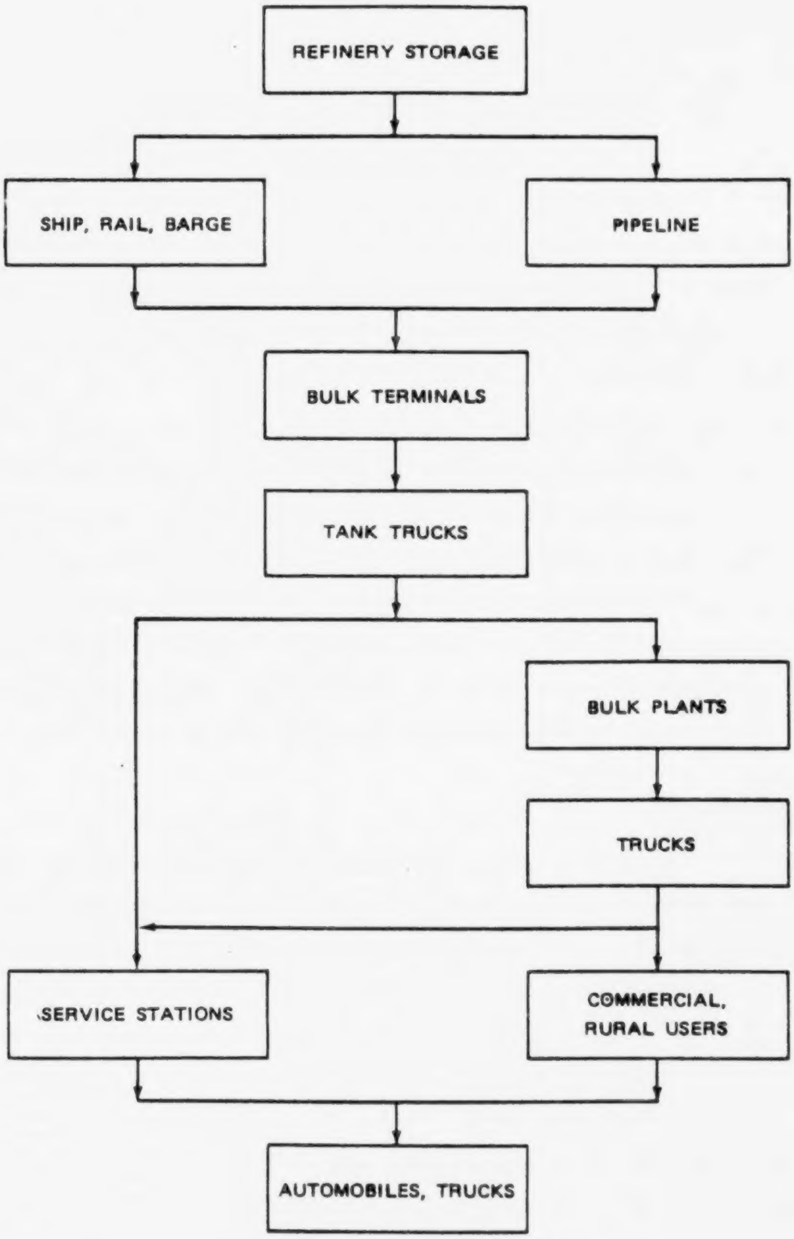

REFINERY STORAGE
SHIP, RAIL, BARGE
PIPELINE
BULK TERMINALS
TANK TRUCKS
BULK PLANTS
TRUCKS
SERVICE STATIONS
COMMERCIAL, RURAL USERS
AUTOMOBILES, TRUCKS

SOURCE: PEDCo, 1977

FIGURE VII-1. THE GASOLINE MARKETING DISTRIBUTION SYSTEM IN THE UNITED STATES

Standing emissions are caused by improper fit of the seal and shoe to the vessel shell. Small losses also occur when vapor escapes between the flexible membrane seal and the roof. Withdrawal or wetting losses are caused by evaporation from the tank walls as the roof descends during emptying operations (PEDCo, 1977).

2. Distribution

The gasoline distribution system involving transport from the petroleum refineries to the consumer may also be a significant source of atmospheric benzene (see Figure VII-1). Bulk terminals represent intermediate stations set up to serve near-source regional markets. Gasoline at bulk terminals is transferred directly from refinery by ships, rail tank cars, barges, and pipelines. Bulk plants, on the other hand, are designed for local markets and their supplies are distributed by tank trucks. Service stations that fuel public motor vehicles are supplied by tank trucks from either bulk terminals or bulk plants. Privately owned commercial operations, such as those providing fuel for vehicles of a company fleet, are generally supplied by tank trucks from an intermediate bulk installation.

Most of the emissions take place during transfers of the gasoline to tank trucks. These losses occur at a rate directly proportional to the amount of gasoline passing through the particular location. Because many tank trucks are filled at one bulk terminal or plant, benzene emissions from that procedure are potentially much greater. As empty tank trucks are filled, hydrocarbons in the vapor space are displaced to the atmosphere unless vapor collection facilities have been provided. The quantity of hydrocarbons contained in the displaced vapors depends on the vapor pressure, temperature, method of tank filling, and conditions under which the truck was previously loaded. A schematic drawing of liquid and vapor flow through a typical bulk terminal is found in Appendix A.

All monitoring data collected to date have concerned possible occupational exposures. Measurements at several bulk loading operations in Britain showed ambient benzene concentrations ranging from 0.1 to

7.7 ppm (NIOSH, 1974). In the same study, NIOSH also evaluated worker exposure during loading and weighing of rail tankers with gasoline from storage tanks. An exposure equivalent to 14 ppm over an 8-hr workday was estimated. Thus, environmental exposure to benzene from gasoline distribution systems appears to require some evaluation.

Gasoline is loaded from storage tanks to transport trucks (tank cars) by two basic methods: top loading and bottom loading (PEDCO, 1977). Top loading can be done by splash fill or submerged fill. The former method involves free fall of gasoline droplets and thus promotes evaporation and possibly liquid entrainment of these droplets in the expelled vapors. In subsurface or submerged filling, the gasoline is introduced below the liquid surface in the tank. Bottom loading of gasoline is comparable to submerged top loading.

B. Methodology and Exposures

The emission factors for benzene losses from gasoline storage and transfer are shown in Table VII-1. Because bulk gasoline plants are low-volume operations (4,000 gal/day) and are often located in rural areas, they are not considered in this analysis. Bulk terminals, however, are high-volume operations (250,000 gal/day) and are generally located near urban demand centers--commonly in highly industrialized areas or on city peripheries where population densities are low.

A bulk terminal has at least three storage tanks, one for each grade of gasoline; each tank holds 55,000 bbl each (8.7×10^3 m^3). Rough ambient benzene concentration estimates for the vicinity of bulk terminals were based on emission factors, assumed storage and loading volumes, and the dispersion modeling results discussed in Chapter IV. A typical bulk terminal has the following characteristics: average tank size, 8.7×10^3 m^3; 28-day retention time; three gasoline storage tanks of average size; gasoline loading equaling 250,000 gal/terminal/day; and facility size of 0.01 km^2. The emission rates for each type of control are calculated as follows:

Table VII-1

EMISSION FACTORS FOR BENZENE LOSSES FROM GASOLINE STORAGE AND DISTRIBUTION

Source	Emission Factor (g/gal)	Reference*
Loading		
Uncontrolled	1.14×10^{-2}	1
Controlled	1.14×10^{-3}	2
Storage		
Uncontrolled	4.0×10^{-2}	1
Controlled	4.0×10^{-3}	3

---

*Key to references:
1. Durham, personal communication, 1978.
2. Polglase, personal communication, 1978.
3. Burr, personal communication, 1978.

Uncontrolled Case

Loading

Emission rate = (emission factor) (volume loaded) (day/s)

$$= (1.14 \times 10^{-2} \text{ g/gal}) (2.5 \times 10^{5} \text{ gal/day}) (\text{day}/86{,}400 \text{ s})$$

$$= 3.3 \times 10^{-2} \text{ g/s} \quad .$$

Storage

Emission rate = (emission factor)(number of tanks)(tank volume)(days/s)

$= (4.0 \times 10^{-2}\ \text{g/gal})(3)(2.3 \times 10^{6}\ \text{gal/28 days})(\text{day}/86{,}400\ \text{s})$

$= 1.14 \times 10^{-1}\ \text{g/s}$

Total emission rate = 1.47×10^{-1} g/s

Partially Controlled Case--Controlled Storage, Uncontrolled Loading

Loading emission rate = 3.3×10^{-2} g/s

Storage emission rate = 1.14×10^{-2} g/s

Total emission rate = 4.44×10^{-2} g/s

Controlled Case

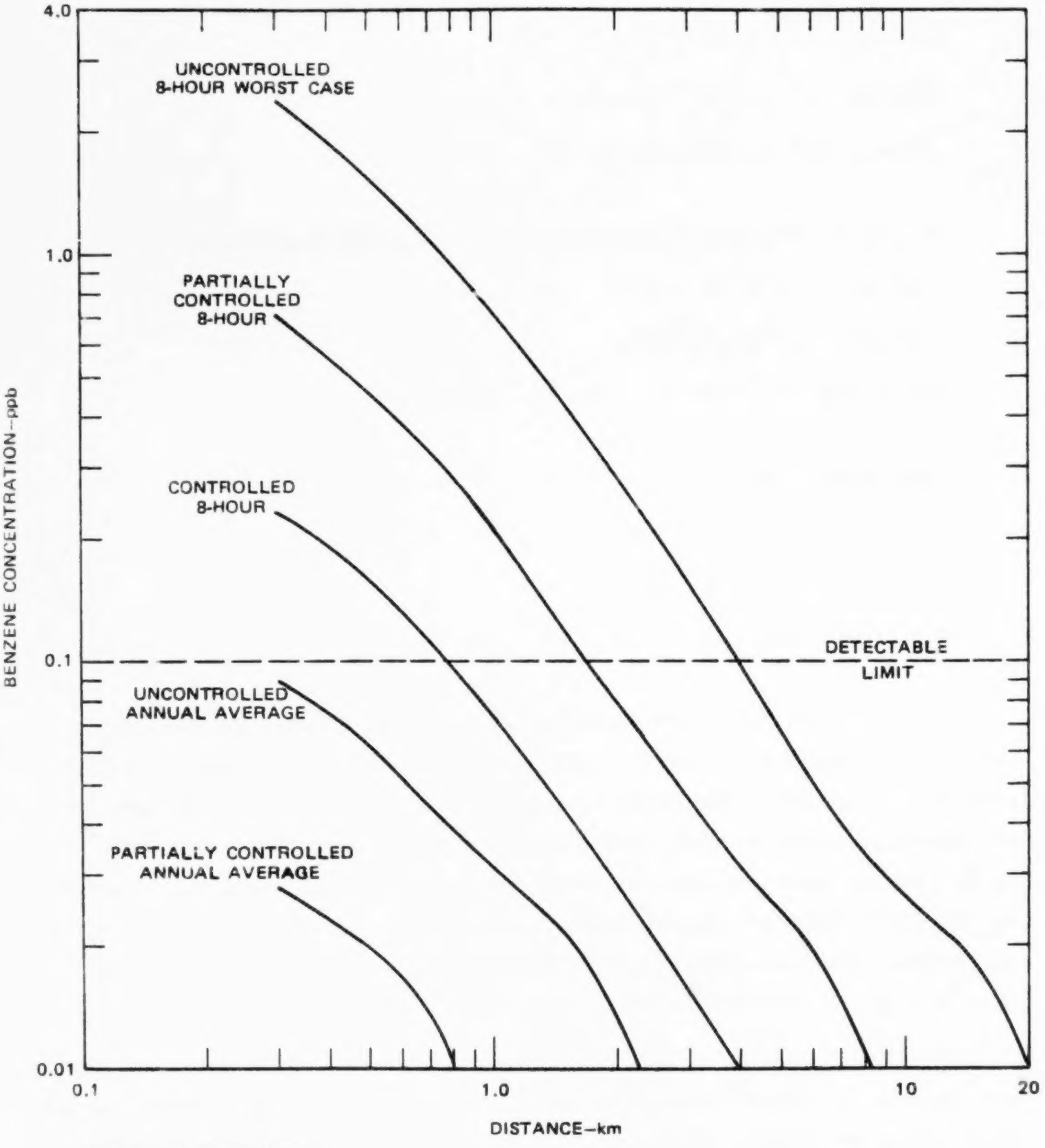
Loading emission rate = 3.3×10^{-3} g/s

Storage emission rate = 1.14×10^{-2} g/s

Total emission rate = 1.47×10^{-2} g/s

The ambient benzene concentrations can be estimated from the dispersion modeling calculations of Youngblood (1977c, 1978) that assume uniform emissions throughout the terminal area. By applying the estimated emission rate to the results presented in Table IV-4 (Chapter IV) for the indicated terminal area of 0.01 km^2, the dispersion curves shown in Figure VII-2 are generated. Note that all annual average concentrations are below the detectable limit. For comparison, the 8-hour worst case is also shown for each type of control.

To determine whether larger operations would cause exposures above the detectable limit, a 10-tank bulk terminal was also evaluated. The characteristics of the facility remain the same, except for gasoline loading of 8.3×10^{5} gal/day and facility size estimated a 0.06 km^2. The calculated emission rates follow:



Source: SRI ESTIMATES

FIGURE VII-2. ESTIMATED DISPERSION CURVE FOR A 3-TANK GASOLINE BULK TERMINAL

Uncontrolled Case

Loading: 1.1×10^{-1} g/s

Storage: 3.8×10^{-1} g/s

Total emission rate = 4.9×10^{-1} g/s

Partially Controlled Case--Uncontrolled Loading, Controlled Storage

Loading: 1.1×10^{-1} g/s

Storage: 3.8×10^{-2} g/s

Total emission rate = 1.5×10^{-1} g/s

Controlled Case

Loading: 1.1×10^{-2} g/s

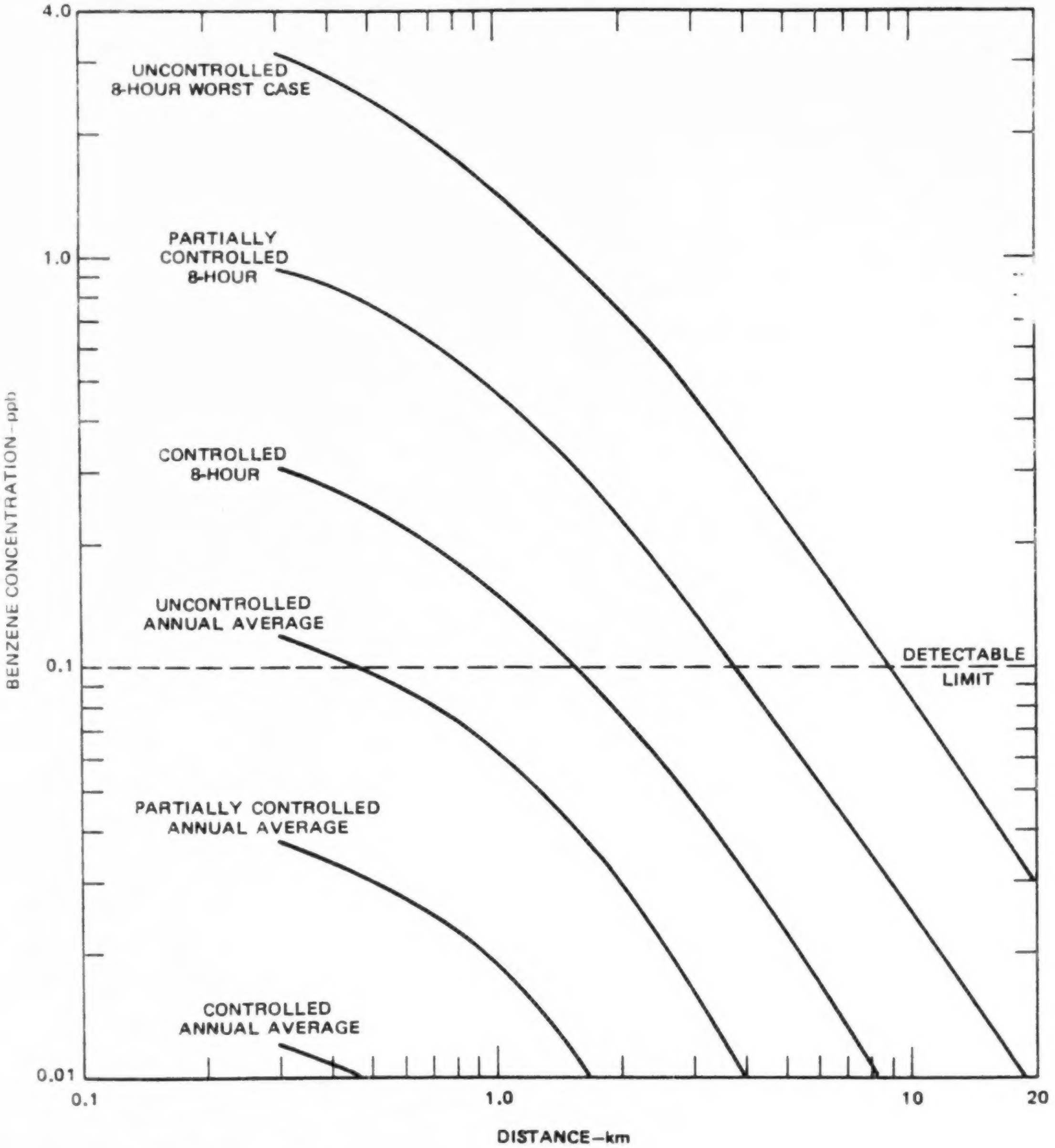
Storage: 3.8×10^{-2} g/s

Total emission rate = 4.9×10^{-3} g/s

The emission rates are again applied to the dispersion modeling results of Youngblood (1977c, 1978) for the 0.06 km^2 dispersion curve (Table IV-4). The dispersion curves shown in Figure VII-3 are then estimated. Annual average concentrations fall below the detectable limit for all cases within 500 m of the bulk terminal facility. Because the facility boundary is estimated to be approximately 200 m on each side, the number of people exposed to annual average concentrations higher than 0.1 ppb is assumed to be minimal.

The results of this analysis indicate that few members of the public are exposed to annual average benzene concentrations higher than 0.1 ppb. As shown, some people are exposed to 8-hour worst case concentrations between 0.1 and 1.0 ppb. Nevertheless, exposures to the public are considered minimal, although occupational exposures may be high.

No information is available about the number of gasoline storage terminals in an average terminal facility. Therefore, the analysis here



Source: SRI ESTIMATES

FIGURE VII-3. ESTIMATED DISPERSION CURVE FOR A 10-TANK GASOLINE BULK TERMINAL

merely shows a range of possible facilities. Although it is not known how many terminals have floating roofs (90-95% more control then fixed roof tanks), estimates are that 70 to 80% of a total of 2700 terminals are controlled in this manner (Burr, personal communication, 1978).

VIII URBAN EXPOSURES

A. Sources

Urban exposures to benzene come from many sources, including chemical manufacturing plants, automobile exhaust, gasoline service stations, gasoline evaporation, and losses through transportation and storage of benzene and gasoline. Because benzene is not routinely monitored in ambient air, few sampling data exist. A study by Altshuller (1969, cited in Mitre, 1976) estimated normal benzene concentrations at between 10 and 50 ppb. This estimate appears to be quite high when compared with other benzene sources discussed previously. In 1973, the General Motors Atmospheric Research Laboratory monitored ambient air quality in Denver for a variety of hydrocarbons. Average benzene concentrations of 3 ppb were found, with a maximum of 30 ppb (Ferman et al., 1977). A study of atmospheric benzene and toluene levels in Toronto found a maximum concentration of 98 ppb, with an average concentration of 13 ppb (Pilar and Graydon, 1973). That study concluded that benzene contamination of the air was related to automobile emissions based on three factors: (1) the ratio of benzene to toluene, (2) the presence of distinct peak periods for both hydrocarbons at rush hour periods, and (3) the relative concentrations detected at various sampling stations.

Research Triangle Institute (1977) collected grab samples in urban areas with high industrial activity (see Table VIII-1). Measured benzene concentrations varied significantly--from a trace to 94 ppb. Some of the reasons for such variation include meteorological conditions, density of automobiles in urban areas, industrial emissions, and sampling periods.

Gasoline contains varying amounts of benzene, depending on lead content and refinery source, among other things. Before 1974, the average benzene content in U.S. gasoline was less than 1% by liquid volume (Runion, 1975). More recent data (Runion, 1976) indicate that the average benzene content has been increased to maintain octane levels as lead

Table VIII-1

RESULTS OF AMBIENT BENZENE MONITORING
IN URBAN AREAS WITH HIGH INDUSTRIAL ACTIVITY

Location	Industrial Activity*	Average Sampling Time (min)	Number of Samples	Average Benzene Concentration (ppb)
Patterson, NJ	A,I	42	1	0.7
Clifton, NJ	A,I	39	1	trace
Passaic, NJ	A,I	39	1	2.0
Hoboken, NJ	A,I	39	1	trace
Newark, NJ	A,I	38	1	94
Staten Island, NY	A,I	37	1	0.7
Edison, NJ	A,I	42	1	1.0
Houston, TX	6C, 5P, 1Co, A	72	3	2.6
Los Angeles, CA	A,I	52	2	5.5
Long Beach, CA	A,I	52	1	7.1
St. Louis, MO & vicinity	1C, 1Co, 1P, A	420	6	18.9
Baton Rouge, LA & vicinity	1C, 1P, A	610	21	1.0

---

*Where known, benzene production or consumption facilities are listed.

Key: A = large automobile emission; I = general industrial activity; C = chemical manufacturers using benzene; Co = coke oven; P = petroleum refinery.

Source: Research Triangle Institute, 1977.

content has been reduced. Current estimates of average benzene content in gasoline range from 1.24 to 2.5% by liquid volume (PEDCo, 1977). Tables VIII-2 and VIII-3 show the results of analyses of gasoline from different refinery sources; these results indicate substantial variation among refineries and types of blends.

Table VIII-2

TYPICAL LIQUID VOLUME-PERCENT OF BENZENE IN
GULF U.S. GASOLINES, OCTOBER 1976

	Vol% Benzene		
Refinery Source	Good Gulf	Gulf Crest	No-Nox
A	0.54	0.88	1.16
B	1.99	1.45	0.85
C	1.19	1.21	0.81
D	1.59	1.18	1.49
E	1.25	1.98	2.39
F	0.85	0.82	0.88
Average	1.24	1.25	1.26
Standard deviation	0.52	0.43	0.61

Source: Runion, 1976 (cited in PEDCo, 1977).

Gasoline is a mixture of a wide variety of hydrocarbons and fuel additives. Emissions from gasoline evaporation or exhaust contain many chemical compounds, some of which have demonstrated toxic and/or carcinogenic properties. For example, concern has already been raised about three fuel additives: tetraethyl lead, ethylene dibromide, and ethylene dichloride. Appendix E lists more than 100 hydrocarbons and an equal number of fuel additives commonly found in gasoline. Few data have been generated to quantify possible exposures to these chemical compounds. Such estimates are difficult because of the significant variation among refinery blends.

Table VIII-3

BENZENE CONCENTRATION IN DIFFERENT GRADES AND SEASONAL BLENDS OF GASOLINE

Company-- Typical Service Station	Gasoline Grade	Vol% Benzene in Bulk Sample		Average Vol% Benzene
		Summer	Winter	
Tresler-Comet	Premium	1.11	1.10	1.11
	Regular	1.21	1.00	1.11
	Unleaded	1.41	1.60	1.51
Bonded	Regular	0.88	0.88	0.88
	Unleaded	1.19	1.60	1.40
Bonded	Regular	0.88	0.88	0.88
	Unleaded	1.20	1.60	1.40
Clark	Regular	0.97	2.00	1.49
	Unleaded	1.09	1.10	1.10

Source: National Institute of Occupational Safety and Health, 1976 (cited in PEDCo, 1977).

To determine average urban exposures throughout the United States, it is necessary to restrict the analysis. Although substantial variation probably occurs from one urban area to another, it is nonetheless possible to determine a reasonably accurate estimate of annual average exposures related to two definitive sources: evaporative losses at service stations and automative emissions from tailpipe emissions and evaporative losses.

B. Methodology and Exposures

1. Urban Exposures from Automobile Emissions

The benzene content in gasoline varies widely, with an average of approximately 1.24% by liquid volume. In addition, catalytic converters on automobiles can reduce benzene in vehicle exhaust by 30 to 80% (Johnson, 1977). Thus, similar variation in benzene emitted to the atmosphere can be expected from evaporation of gasoline and from vehicle exhaust emissions.

EPA has conducted dispersion modeling of automobile emissions. In the Hanna-Gifford dispersion model used by Schewe of EPA (1977), concentration depends on areawide emissions and wind speed. An empirical factor is also applied. By applying generalized emission factors, areawide emissions were estimated from vehicle miles traveled (the total number of miles traveled in a given area in a year by all automobiles) and from the number of registered automobiles. Table VIII-4 presents the results of this study. In central cities, the concentrations range from 1.0 ppb to 4.0 ppb, whereas in suburban areas the concentrations are generally below 1.0 ppb.

Limited data are available concerning urban exposures from automobile emissions. Consequently, it is difficult to develop accurate techniques to predict benzene levels in urban areas. Uncertainties include: benzene content in gasoline; control technology; deterioration of the control technology over time; and dispersion characteristics of benzene under variable meteorological conditions. Thus, a simplified model is employed to provide general estimates of ambient concentrations.

The Hanna-Gifford dispersion model (Gifford and Hanna, 1973) as applied by Schewe (1977) is used for this analysis. Inputs to the model include: number of vehicle registrations, total number of vehicle miles traveled (VMT), area size, and average annual wind speed.

The tailpipe emissions are estimated by the following equation (Schewe, 1977):

$$Q_{tail}(\mathrm{g/s\text{-}m^2}) = \frac{0.22\ \mathrm{g}}{\mathrm{mile}}\ \frac{\mathrm{VMT}}{\mathrm{s}}\ \frac{1}{\text{Area of study } (\mathrm{m^2})} \qquad (8.1)$$

The emission factor of 0.22 g benzene per mile is a composite emission factor for 1976 (Schewe, 1977).

The evaporative emissions are calculated as follows:

$$Q_{evap}(\mathrm{g/s\text{-}m^2}) = \frac{0.148\ \mathrm{g}}{\mathrm{trip}}\ \frac{3.3\ \mathrm{trips}}{\mathrm{veh.\ \text{-}day}}\ \frac{\#\ \mathrm{veh.}}{1}\ \frac{365\ \mathrm{days}}{\mathrm{year}}\ \frac{\mathrm{year}}{3.154 \times 10^7\ \mathrm{s}}\ \frac{1}{\mathrm{area}} \qquad (8.2)$$

Table VIII-4

ESTIMATES OF ANNUAL AVERAGE BENZENE CONCENTRATIONS IN FOUR URBAN AREAS

City	10^9 Vehicle Miles Traveled	Registered Automobiles	Land Area (10^8 m^2)	Q_{evap} (10^{-9} g/s m^2)	Q_{tail} (10^{-9} g/s m^2)	Q_T (10^{-9} g/s m^2)	Average Annual Wind Speed (m/s)	Benzene Concentration	
								(μg/m^3)	(ppb)
Dallas									
City	6.14	619,684	6.9	5.08	62.2	67.3	5	3.03	.95
Suburbs	5.36	540,786	43.0	.719	8.80	9.52		0.43	.13
Los Angeles									
City	10.2	2,044,203	12.0	9.63	59.3	68.9	2	7.75	2.4
Suburbs	21.5	4,299,073	54.0	4.53	28.0	32.5		3.66	1.1
St. Louis									
City	2.86	378,280	1.6	13.5	126.0	140.0	4	7.88	2.5
Suburbs	7.71	1,020,219	61.0	.944	8.80	9.74		0.55	.17
Chicago									
City	18.8	1,860,292	5.8	18.2	227.0	245.0	4	13.78	4.3
Suburbs	23.5	2,327,206	88.0	1.49	18.6	20.1		1.13	.35

---

*1976 projections

Q_{evap} = Evaporative emissions from automobiles.

Q_{tail} = Tailpipe emissions from automobiles.

Q_T = Total automobile emissions

Source: Schewe, 1977

By multiplying the constants in this equation, we get the following:

$$Q_{evap}(g/s\text{-}m^2) = \frac{5.653 \times 10^{-6}\ g}{veh.\ s}\ \frac{\text{number of vehicles}}{\text{area of study } (m^2)} \qquad (8.3)$$

This technique assumes that each vehicle emits 0.148 g of benzene per trip and that the average vehicle travels 3.3 trips per day (Schewe, 1977).

The total emissions for automobiles can be expressed as follows:

$$Q_T = Q_{tail} + Q_{evap} \qquad (8.4)$$

Equation (8.4) is essentially the summation of Equations (8.1) and (8.3).

To calculate the average annual areawide benzene concentrations, Equation (8.5) is used:

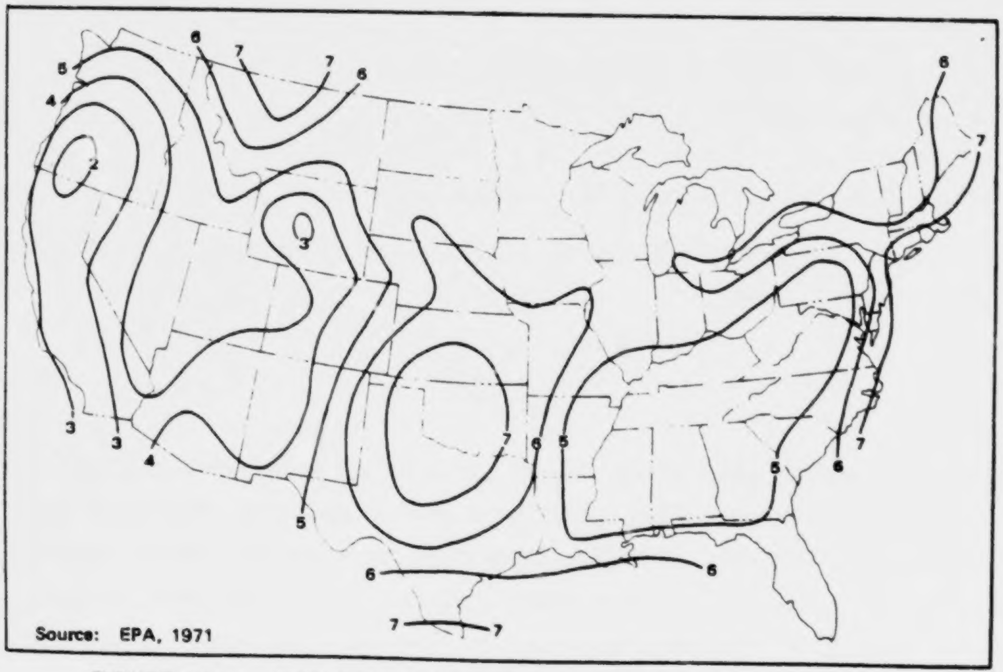
$$\chi_A = \frac{225\ Q_T}{u\ (m/s)} \qquad (8.5)$$

The average annual wind speed, u, in the area of study was obtained from Figure VIII-1. Because wind speed (and thus dispersion) increases in the afternoon, the morning values were used to estimate higher concentrations. The number 225 is an empirical factor derived from several studies that gave very good results for long-term averages; it applies to light-duty vehicles such as passenger cars.

Because of the general unavailability of 1976 data for all urban areas, 1973 data were used as much as possible in this estimation. Comparisons of 1973 with 1976 data indicated that the changes was less than 3% and had a negligible effect on the final results. The following data sources were used:

- 1973 Standard Metropolitan Statistical Area (SMSA) and county populations--U.S. Bureau of the Census, 1976, Series P-25, No. 618.
- 1973 SMSA and county automobile registrations--U.S. Department of Transportation, Federal Highway Administration, 1974, Table MV-21.

- Average annual vehicle miles traveled by size of SMSA--Federal Highway Administration, 1972, Nationwide Personal Transportation Study, Report No. 2, Table 9.
- Average annual wind speed--EPA, 1972, Publication No. AP-101.
- SMSA, county and city land areas--Bureau of the Census, 1972 County and City Data Book.



Source: EPA, 1971

FIGURE VIII-1. ISOPLETHS (m/sec) OF MEAN ANNUAL WIND SPEED THROUGH THE MORNING MIXING LAYER

A detailed analysis was conducted for the six largest cities in the U.S. (populations of more than 1 million). Table VIII-5 presents the results. Because input data were slightly different, the results differ somewhat from those shown in Table VIII-4. For example, the suburban area used in this estimate may include a larger area than that used in the Schewe estimates. Suburban areas are defined as those areas outside the central city but within the SMSA. Because no VMT and registration data were available at the city level, they were extrapolated either from SMSA data or county data and were based on the fraction of the population residing

Table VIII-5

ESTIMATES OF AVERAGE ANNUAL BENZENE CONCENTRATIONS FOR CITIES WITH POPULATION EXCEEDING 1,000,000

City	SMSA Population 10^3	City Population 10^3	Ci Area 10^9 m^2	Automobile Registration	VMT/ vehicle 10^3	VMT 10^{10}	u (m/s)	Q_{tail} 10^{-7} g/s-m^2	Q_{evap} 10^{-8} g/s-m^2	Q_T 10^{-7} g/s-m^2	Benzene Concentration			
											Central µg/m^3	City ppb	Suburban ppb	Composite ppb
Chicago	6,999.8	3,173	0.57	1,324,171	11.5	1.5	5	1.8	1.3	1.9	8.6	2.7	1.1	1.9
Detroit	4,446.3	1,387	0.35	675,065	11.5	0.77	6	1.5	1.0	1.6	6.0	1.8	1.2	1.5
Houston	2,163.4	1,320	1.1	701,766	14.0	0.98	6	0.63	0.36	0.66	2.5	0.7	0.23	0.5
Los Angeles	6,938.3	2,747	1.2	1,490,483	11.5	1.7	3	0.98	0.67	1.0	7.5	2.3	0.4	1.3
New York	9,746.4	7,647	0.77	1,707,891	11.5	1.9	7	1.7	1.2	1.8	5.9	1.8	0.3	1.0
Philadelphia	4,826.3	1,862	0.33	944,660	11.5	1.0	6	2.0	1.5	2.1	8.0	2.5	1.5	2.0

Source: SRI estimates based on Hanna-Gifford model as applied by Schewe (1977); data sources listed in text.

in each area. The results show that the estimated benzene concentrations in city and suburban areas range from 0.7 to 2.7 ppb and 0.2 and 1.5 ppb, respectively. The composite benzene concentrations in the six corresponding SMSAs ranged from 0.5 to 2.0 ppb.

It is expected that people living in urban areas are exposed to higher levels of benzene from automotive emissions than those living in rural areas. Consequently, our approach was designed to include as many urban residents as possible. Although 43% of the total urban population resides in central cities (as defined by the Bureau of the Census), 83% of the total urban population resides in SMSAs. Thus, a greater percentage of the urban population is captured by using SMSAs as study areas. The six largest cities are in SMSAs with more than 2 million population. To analyze the remaining SMSAs, the following population size categories were employed (U.S. Bureau of the Census, 1976, Series P-25, No. 618):

SMSA Population Size Category	Number of Areas
2,000,000 or more	15
1,000,000 - 2,000,000	20
500,000 - 1,000,000	37
250,000 - 500,000	63
less than 250,000	124

SMSA composite benzene concentrations were estimated for seven areas that represent four population size categories (see Table VIII-6). For SMSAs with population exceeding 500,000, the composite average annual benzene concentrations ranged between 0.1 and 0.4 ppb. However, SMSAs of less than 500,000 were below 0.1 ppb. It may be assumed from this analysis that the SMSAs with population less than 500,000 have average annual benzene concentrations less than 0.1 ppb.

The estimates of urban exposures from automobile emissions are order-of-magnitude estimates that are based on a simple dispersion model. Note that, in certain locations and under certain meteorological conditions, benzene concentrations may be a factor of 10 higher than those listed.

Table VIII-6

ESTIMATES OF AVERAGE ANNUAL BENZENE CONCENTRATIONS FOR SELECTED SMSAs

SMSA	Population	Area (m^2)	Automobile Registration	VMT/ Vehicle 10^3	VMT 10^9	u m/s	Q_{tail} 10^{-9} $g/s\text{-}m^2$	Q_{evap} 10^{-10} $g/s\text{-}m^2$	Q_T 10^{-9} $g/s\text{-}m^2$	Benzene Concentration $\mu g/m^3$	Benzene Concentration ppb
SMSAs > 2,000,000											
Pittsburgh	2,333,600	7.8×10^9	2,358,600	11.3	26.0	5	23.0	17.0	25.0	1.1	.4
San Francisco	3,135,900	6.2×10^9	688,300	11.5	7.7	3	8.5	6.2	9.1	.68	.2
SMSAs 1,000,000 - 2,000,000											
Columbus	1,055,900	6.2×10^9	567,803	11.3	6.4	5	7.2	5.1	7.8	.35	.1
Milwaukee	1,423,200	3.7×10^9	642,531	11.3	7.2	5	13.0	9.8	14.0	.62	.2
SMSAs 500,000 - 1,000,000											
Sacramento	851,300	8.7×10^9	439,803	11.3	4.9	3	3.9	2.8	4.2	0.3	0.1
Providence-Warwick-Pawtucket	854,400	2.4×10^9	869,100	11.3	9.8	7	28.0	20.0	30.0	0.9	0.3
SMSAs 250,000 - 500,000											
Wichita	375,600	6.2×10^9	221,715	10.3	2.3	7	2.5	2.0	2.7	.08	< 0.1
Harrisburg	425,500	4.1×10^9	198,997	10.3	2.0	5	3.4	2.7	3.7	.16	< 0.1

Source: SRI estimates using Hanna-Gifford dispersion model as applied by Schewe (1977).

In addition, central city areas (as shown in Table VIII-5) may have consistently higher levels than surrounding areas because of traffic density, frequency of intersections, and street density. Because the model only includes automobile emissions, areas with substantial commercial or bus transportation may have higher levels than estimated. Also, the model is extremely sensitive to area size as Table VIII-5 indicates. Thus, composite SMSA benzene concentrations provide the most reasonable estimate of the average annual exposures for an urbanized area.

The total estimated urban population exposed to benzene in concentrations greater than 0.1 ppb from automobile emissions is shown in Table VIII-7. The 1974 SMSA populations for Chicago, Detroit, Los Angeles, New York, and Philadelphia were summed to estimate the population exposed to average annual benzene concentrations of 1.1 to 4.0 ppb. The 1974 SMSA population of Houston plus the remainder residing in SMSAs with populations greater than 500,000 were summed to estimate the total population exposed to average annual benzene concentrations between 0.1 and 0.1 ppb. The results indicate that 114 million people, or 73% of the total SMSA population, are exposed to average annual benzene concentrations greater than 0.1 ppb.

Table VIII-7

URBAN POPULATION EXPOSURES RELATED
TO AUTOMOBILE EMISSIONS

	Annual Average Benzene Concentration (ppb)*		
Source	0.1-1.0	1.1-4.0	Total
Automobile emissions	69,000,000	45,000,000	114,000,000

---

*To convert to $\mu g/m^3$, multiply concentrations by 3.2; to estimate 8-hour worst case, multiply by 4.1.

Source: SRI estimates.

2. Urban Exposures from Gasoline Service Stations

People residing in the vicinity of service stations are exposed to benzene emissions from evaporative losses resulting from gasoline pumping by attendants and customers, and from gasoline loading into underground tanks by distribution trucks. The amount of benzene emitted depends on a number of critical factors: ambient temperature, vapor recovery controls, pumping volumes, and the benzene content in gasoline are probably the most important. The United States has approximately 184,000 service stations, and it is expected that many people are exposed to benzene from these sources. Because the density of service stations in urban areas is high, only urban areas are considered in this analysis.

For the population exposed to service station emissions, it is necessary to estimate the stations in urban areas. Service station density can be extrapolated from data presented in Table VIII-8. These data, which have no apparent regional pattern, show an average of 0.7 service station per 1000 population. This density figure can be applied generally to urban areas throughout the United States to give a rough approximation of the total number of service stations. Urbanized areas[*] provide the best population base. The 1970 population residing in urbanized areas was 118,447,000 (Bureau of Census, 1975). Thus, service stations in urbanized areas are estimated at 83,000, or 46% of all stations.

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[*] Defined by the Bureau of Census as the central city or cities and surrounding closely settled areas. Sparsely settled areas in large incorporated cities are excluded by this definition. Densely populated suburban areas, however, are included (U.S. Department of Commerce, Bureau of the Census, 1972 County and City Data Book).

Table VIII-8

SERVICE STATION DENSITY IN FOUR METROPOLITAN AQCRs

AQCR	Number of[*] Service Stations (1977)	AQCR[†] Population (1975)	Service Station[‡] Density (number/1000 population)
Boston	2,353	4,039,800	0.6
Dallas	3,218	2,970,900	1.1
Denver	1,277	1,389,000	0.9
Los Angeles	7,298	14,072,400	0.5

Sources: * ADL

† U.S. Department of Commerce, Bureau of Economic Analysis, 1973.

‡ SRI estimates.

The atmosphere in the vicinity of gasoline service stations has been monitored in three studies. API (draft report, 1977) monitored eight service stations in various geographic locations with continuous samplers over a 24-hour period. Quality control information is not available for these data. Six of the monitored locations were in urban or suburban areas.[*] The average benzene concentrations ranged from 3 to 10 ppb within 200 m of the service station (see Figure VIII-2). The two locations in rural or mountain areas showed generally lower average benzene concentrations ranging from 0.4 to 3.7 ppb within 200 m of the service station (see Figure VIII-3). The wide variability in the data is probably related to the differing meteorologic conditions, pumping volume, benzene concentration in the gasoline, and ambient temperatures.

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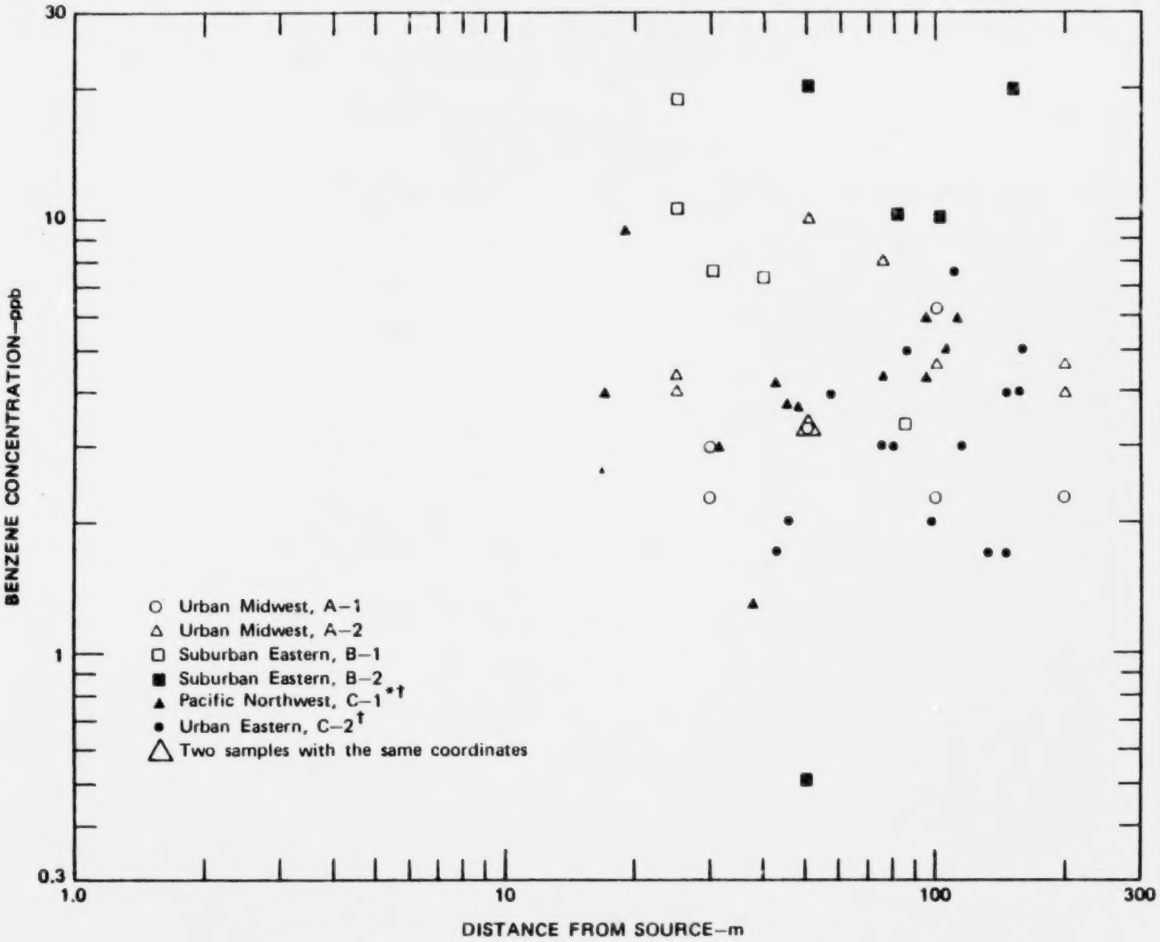
[*] The Pacific Northwest location (C-1) was included in this category because of its proximity to an interstate highway and commercial development.

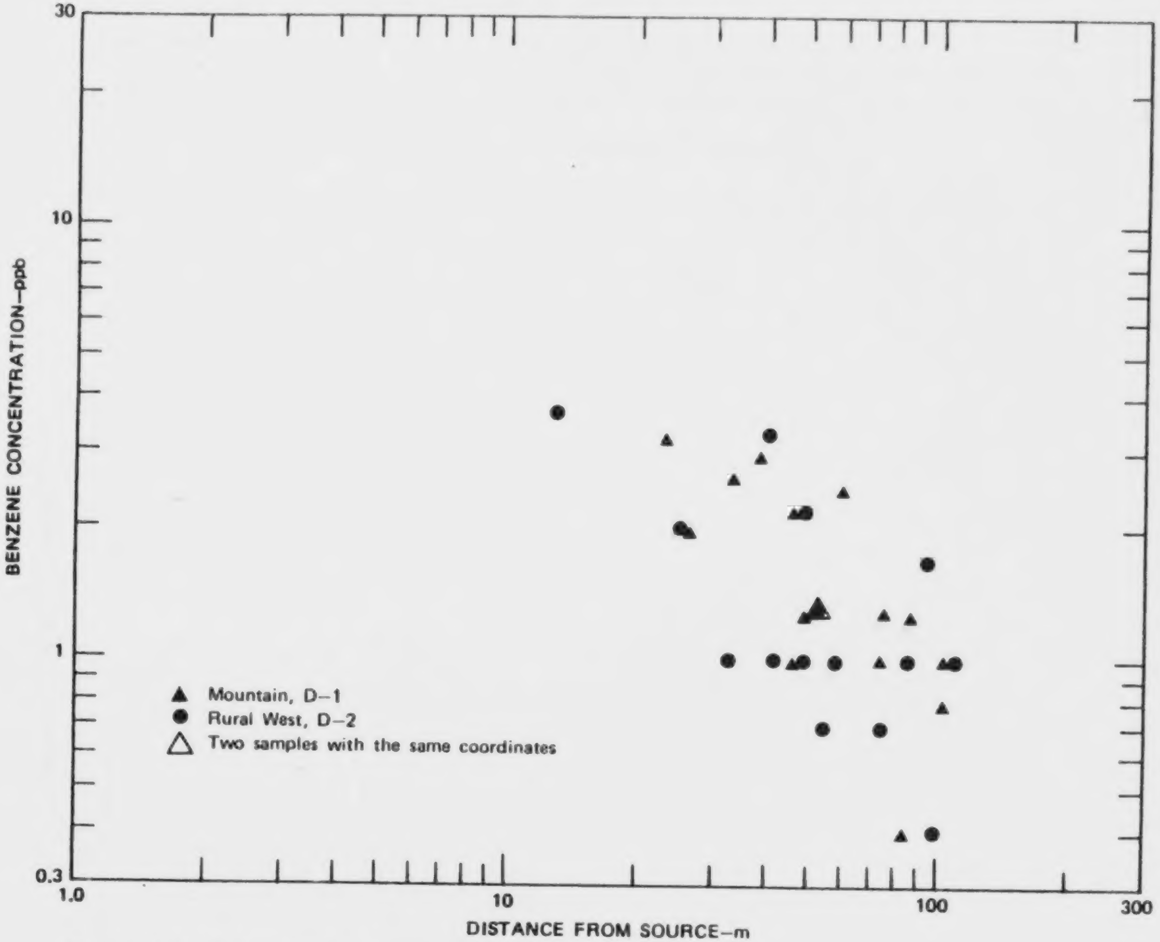


* Because this location was next to an interstate highway, these sampling data were included in this category.

† Distances from the source were recalculated from the original data for these locations. The distances shown here represent distances from the gasoling pumps. The original data showed distance from the service station.

Source: Adapted from American Petroleum Institute, 1977

FIGURE VIII-2. RESULTS OF ATMOSPHERIC MONITORING IN THE VICINITY OF URBAN–SUBURBAN GASOLINE SERVICE STATIONS, SUMMER, 1977



Source: Adapted from American Petroleum Institute, 1977

FIGURE VIII-3. RESULTS OF ATMOSPHERIC MONITORING IN THE VICINITY OF RURAL-MOUNTAIN GASOLINE SERVICE STATIONS, SUMMER, 1977

Battelle (1978a) monitored the atmosphere for benzene in the vicinity of gasoline service stations in the summer of 1977. The results for the three locations in Columbus, Ohio, gave average concentrations ranging from 1.0 to less than 1.0 ppb for a 24-hour period. However, the report urges caution in using these data because of unexplained variations from expected results. The only finding that the report could report with assurance was that benzene concentrations did seem to decrease with distance from the service stations. Benzene concentrations ranged from 10 to 22 ppb 150 m downwind in two grab samples obtained in a residential neighborhood during the filling of an underground storage tank.

Radian Corporation monitored the atmosphere for benzene in the vicinity of a gasoline distribution facility in Irving, Texas, for Shell Oil Company (Radian, 1978). The report does not indicate whether the facility was a service station or a gasoline bulk plant. Ten 24-hour samples were collected at the first site 800 m from the facility on top of a two-story motel; they showed an average benzene concentration of 2 ppb. At the second site, approximately 180 m from the facility at ground level, the average benzene concentration from 24-hour samples was 3 ppb. These results would seem to indicate that the facility was responsible for adding approximately 1 ppb to the atmosphere. A third sample site approximately 2000 m from the facility and located near a major highway showed a 7 ppb average for two parallel 24-hour samples. (One sample showed 3 ppb; the second backup sample showed 10 ppb; no reasons was offered for the discrepancy between the two samples.)

Separating population exposures related to gasoline service stations from general urban exposures is difficult. Service stations, which are usually located along well-traveled roads, may be isolated or located near other stations. Emissions from service stations vary, based on differences in operating times, pumping volumes, and benzene concentration in gasoline. Benzene concentrations measured at atmospheric monitoring stations are influenced by all of these factors, in addition to emissions from automobile exhaust, evaporation of gasoline from parked cars, and emissions for other benzene point sources. With conditions varying from station to station, nationwide benzene exposure levels from this source are difficult to approximate.

Because gasoline service stations represent a significant source of benzene exposure to many people, we attempted to estimate the exposure levels and the population-at-risk insofar as possible given the data limitations. Three methods, which are discussed below, were investigated.

Point Source Dispersion Modeling--EPA conducted dispersion modeling for a worst-case condition (Youngblood, 1977d) by using the single source (CRSTER) model. Meteorological data for Denver, Colorado, were used to represent a reasonable worst-case location. The model was executed to eliminate nighttime inversions, resulting in enhanced dispersion and, for low-level sources such as service stations, lowered ground-level concentrations. Table VIII-9 presents the results of the dispersion modeling.

In applying the available modeling data to urbanized areas, many difficulties are inherent. Note that the operating conditions, pumping volumes, and the chosen location represent worst-case conditions. In particular, the pumping volume used is approximately four times larger than that for a typical service station. Consequently, extrapolating these results to average conditions is difficult. The data seem to indicate, however, that individuals residing within 100 m of a service station may be exposed to annual average concentrations of 1.0 ppb or more, wheras those residing beyond 100 m may be exposed to less than 1.0 ppb on an annual average basis.

Uniform Distribution Dispersion Modeling--Because initial efforts to treat service stations as point sources gave unsatisfactory results, we decided to assume that service stations were uniformly distributed and to use the Hanna-Gifford dispersion model to estimate annual average concentrations. This model should be applicable because service stations are widely distributed throughout urbanized areas. (We estimate 1.5 service stations per square kilometer, i.e., 2.4 per square mile.)

Table VIII-9

ROUGH DISPERSION MODELING RESULTS FOR GASOLINE SERVICE STATIONS

Station[*]	Hours of Operation	% Benzene In Gasoline Vapor	Calculated Emission Rate (g/s)	Distance (m)				
				50	100	150	200	300
				8-Hour Worst-Case Concentration (ppb)[**]				
A1	8 a.m. - 4 p.m. 6 days/week	0.7	0.019	27	13	8	5	3
A2	8 a.m. - 4 p.m. 6 days/week	3.0	0.080	117	57	34	23	12
				Annual Average Concentration (ppb)[**]				
B1	24 hours/day 7 days/week	0.7	0.0053	1	<1	<1	<1	<1
B2	24 hours/day 7 days/week	3.0	0.023	2	1	1	<1	<1

---

[*] Pumping rate for all stations is 200,000 gal/month uniformly over hours of operation; rate of evaporative loss for all stations is 10 g/gal pumped.

[**] To convert to $\mu g/m^3$, multiply concentrations by 3.2.

Source: Youngblood, 1977d.

The same approach used in the previous section was applied here: Total emissions related to evaporation from gasoline service stations were estimated for an area. This result was used as the input to the dispersion equation [Equation (8.5)], along with wind speed for the region. The emission factors were determined through consultation with EPA and are summarized in Table VIII-10. We assumed that 50% of the service stations have submerged fill and 50% have splash fill. The estimates of controlled emissions assume no change in breathing and spilling losses from the uncontrolled situation.

Table VIII-10

EMISSION FACTORS FOR BENZENE LOSSES AT GASOLINE SERVICE STATIONS

	Hydrocarbon Emissions			
Type of Control	Gasoline Storage and Fill (g/gal)	Automobile Filling (g/gal)	Total (g/gal)	Estimated Benzene Emissions* (g/gal)
Uncontrolled	4.8	4.4	9.2	0.07
Stage I (controls on gasoline storage/filling operations	0.59	4.4	5.0	0.04
Stages I and II (controls on gasoline storage/ filling and on automobile refueling	0.59	0.73	1.32	0.01

---

*Hydrocarbon emissions are estimated to contain 0.8% benzene, assuming 1.3% benzene by liquid volume in gasoline.

Source: Kleeburg, personal communication, 1978.

Currently, Stage I controls are required in 13 AQCRs: Boston, New Jersey-New York, New Jersey-Philadelphia, Pittsburgh, Baltimore, Washington, D.C., Houston, San Antonio, Denver, Indianapolis, Los Angeles, and California's Sacramento and San Joaquin Valleys. Stages I and II controls have only been implemented in the San Francisco Bay Region and in approximately 30% of San Diego service stations. The California Air Resources Board plans to implement Stage II controls in four additional AQCRs (Perry, personal communication, 1978).

Separate calculations were made for (1) urbanized areas with uncontrolled service stations, (2) Stage I controls, and (3) Stages I and II controls. Because AQCRs cover a larger area than do urbanized areas, it was necessary to determine the population and land area of all the urbanized areas within a particular AQCR. For example, the New Jersey-Philadelphia AQCR contains the urbanized areas of Philadelphia, Trenton, New Jersey, and Wilmington, Delaware (U.S. Bureau of the Census, 1972 County and City Data Book; Bureau of Economic Analysis, 1973). The average U.S. wind speed was determined by weighting regional average wind speeds by population (see Table VIII-11). Total gallons of gasoline in urban areas was estimated at 4.0×10^{10} gallons, based on the 1975 urban miles traveled by passenger cars (600×10^{9} miles) and an average of 13.74 miles per gallon (U.S. Bureau of Census, 1977 Statistical Abstract).

The results of this analysis are shown in Table VIII-12. Note that the estimated levels are more than 1 order of magnitude below concentrations measured by atmospheric monitoring. Several reasons may account for this. As previously mentioned, the Hanna-Gifford dispersion model is sensitive to land areas. We also assumed uniform distribution of service stations, when in reality they are often clustered in groups of three or more in one location. In addition, more service stations are located in central city areas than suburban areas.

Table VIII-11

DETERMINATION OF WEIGHTED U.S. AVERAGE WIND SPEED

Census Bureau Region	1970 Population (10^3)	Percent of Total	Average Wind Speed (m/s)	Wind Speed Component
Northeast	11,883	5.8	6.5	0.4
Mid-Atlantic	37,274	18.3	6.5	1.2
E. North Central	40,313	19.8	5.5	1.1
W. North Central	16,518	8.1	6.0	0.5
South Atlantic	30,805	15.1	5.5	0.8
E. South Central	12,839	6.3	5.0	0.3
W. South Central	19,388	9.5	6.0	0.6
Mountain	8,348	4.1	4.0	0.2
Pacific	26,600	13.0	3.0	0.4
Total	203,806	100.0		5.5

Average Weighted U.S. Wind Speed = 5.5 m/s.

Source: U.S. Bureau of Census, 1975 Statistical Abstract; Figure VIII-1; and SRI estimates.

Table VIII-12

ESTIMATES OF ANNUAL AVERAGE BENZENE CONCENTRATIONS IN URBAN AREAS FROM GASOLINE SERVICE STATIONS BASED ON THE HANNA-GIFFORD DISPERSION MODEL

Type of Control	Exposed Urban Population (10^6)	% of Total Urban Population	Estimated Gallons Pumped/Year (10^{10})	Land Area (10^3 km^2)	Benzene Emission Factor (g/gal)	Benzene Emission Rate (g/s)	Estimated Annual Average Benzene Concentrations (ppb)*
Uncontrolled	68.4	58	2.55	39.3	0.07	60	0.06
Stage I	45.4	38	1.7	15.5	0.04	20	0.05
Stages I and II	4.5	4	0.18	1.7	0.01	0.6	0.03†

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*To estimate μg/m^3, multiply by 3.2.

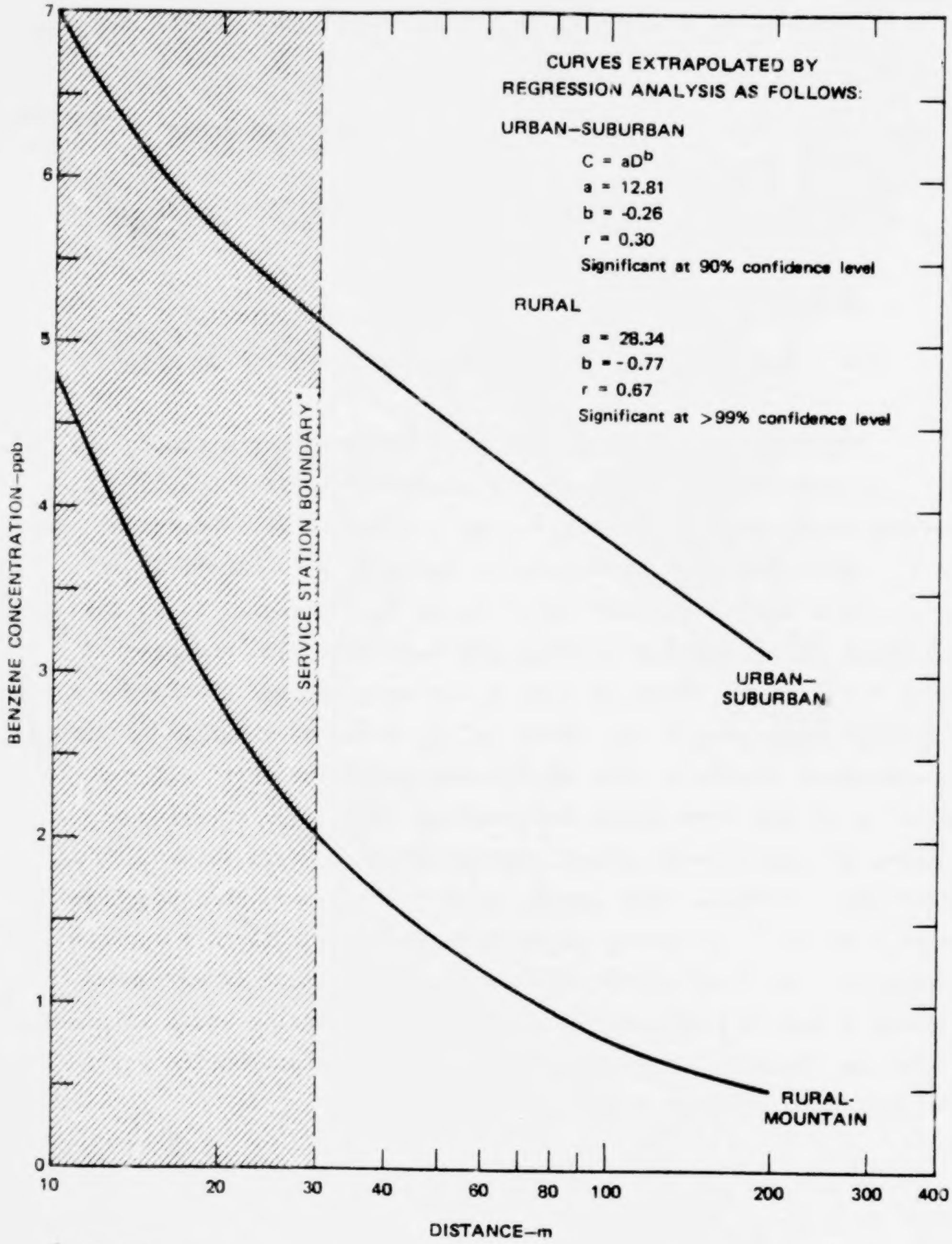
†Because both locations with Stages I and II controls are on the West Coast, the average wind speed of 3 m/s was used for this calculation. If the U.S. weighted average of 5.5 m/s was used instead, the estimated concentration would be 0.01 ppb.

Source: SRI estimates

Application of the Monitoring Data--Atmospheric monitoring in the vicinity of gasoline service stations seems to indicate that their contribution to the urban atmosphere ranges from 1 to 2 ppb within 100 m of the station. Because of the extent and geographic coverage of the API monitoring data, those data were analyzed further to determine whether they could be applied to other urban areas.

Regression analysis was used to fit a curve to the two sets of data shown in Figures VIII-2 and VIII-3. As Figure VIII-4 indicates. fairly good agreement was achieved between the two. Excellent correlation was noted for the curve representing rural-mountain service stations. Benzene concentrations ranged from 2 ppb at the station boundary to 0.5 ppb at 200 m from the station. The urban-suburban curve, on the other hand, showed concentrations ranging from 5 ppb at the station boundary to 3 ppb at 200 m. Correlation of this curve (r = 0.30) with the monitoring data was not as good as the correlation of the rural-mountain curve (r = 0.67), in part because benzene concentrations in urban areas are influenced by many sources other than gasoline service stations. The difference between the two curves ranges from 2.5 to 3 ppb and can be considered to be the background concentration associated with urban areas. This assumption correlates well with other monitoring data and dispersion modeling of urban areas discussed previously in this chapter.

The rural-mountain curve should represent the contribution of benzene to the urban atmosphere in the absence of other influencing benzene sources. This curve was used in estimating the population exposed to benzene from gasoline service stations. For purposes of extrapolation, the population residing between 30 and 80 m from a service station is assumed to be exposed to annual average benzene concentrations between 1 and 4 ppb. Those residing from 80 to 300 m from a service station are assumed to be exposed to between 0.1 and 1.0 ppb. Given the available data, precise identification of the point at which the benzene levels drop below 0.1 ppb (the detectable limit) is impossible. Therefore, we assume that a service station's influence on benzene concentrations is minimal beyond 300 m.



* ASSUMED

Source: SRI estimates

FIGURE VIII-4. REGRESSION CURVES DEVELOPED FROM API ATMOSPHERIC MONITORING DATA COLLECTED IN THE VICINITY OF GASOLINE SERVICE STATIONS

The exposed population can be estimated as follows:

1 to 4 ppb

$$(\pi r^2)(\text{number of service stations})(\text{density of urbanized areas}) = \text{exposed population}$$

$$\pi(0.08\ \text{km} - 0.03\ \text{km})^2(83{,}000)(1318\ \text{people/km}^2) = 0.9 \times 10^6$$

0.1 to 1.0 ppb

$$\pi(0.3\ \text{km} - 0.08\ \text{km})^2(83{,}000)(1318\ \text{people/km}^2) = 20 \times 10^6$$

These estimates, which are only rough approximations, are based on assumptions of uniform distribution of service stations in urbanized areas, uniform pumping volumes, and average population density, and on a curve developed by regression analysis of monitoring data. In reality, more service stations are located in commercial areas than in residential areas, pumping volumes vary substantially, and several service stations are often located in the same general area. One service station was monitored at all sites, except one, for which two stations were monitored (based on site maps accompanying the draft API report). However, note that monitoring data are not often a good representation of annual average concentrations because of short-term variations in meteorology, operating conditions, sales volume, and other possible benzene sources in the area. Nevertheless, the correlation appears adequate for our rough approximations. Further study is warranted to determine a more accurate estimate of exposure levels, based on pumping volumes, co-location of service stations, their distribution within an urban area, and emission rates.

IX SELF-SERVICE GASOLINE

A. Sources

Service stations are characterized by their services and business operations: full-service stations, split island stations, self-service stations, and convenience store operations. In full-service stations, attendants offer all services, including gasoline pumping and other mechanical check-ups. If fuel is obtained at any of the last three classes of stations, the customers may fill up their tanks themselves. In split island stations, both self-service and full-service is available. While pumping gasoline, an individual is exposed to high benzene levels released as vapor from the gasoline tank.* Although occupants in the car at both self-service and full-service operations receive some benzene exposures, the highest exposures are received by the individual pumping the gas. Because it is difficult to estimate level and length of exposure for occupants, only those individuals obtaining gasoline from self-service pumps are considered. (It is not within the scope of this report to evaluate occupational exposures.)

Benzene content of evaporative gases increases and decreases during evaporation, depending on the system temperature and the relative volatilities of all the components of the fuel (Mitre, 1976). Recent information indicates that gases released during automobile fill-ups have little relationship to the benzene content in the gasoline. Rather, the ambient temperature relative to the temperature of the gasoline has the most significant effect, and most of the exposure results from the benzene vapor trapped within the tank, not from the gasoline being pumped (Johnson, 1977). If the gasoline is cold relative to the tank (as in summer), most of the benzene vapor will be abosrbed into the gasoline. On the other hand, if the gasoline is warm relative to the tank (as in winter), the benzene vapor will be displaced rather than absorbed and more significant exposures will result.

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*Vapor recovery systems can reduce exposure levels significantly, if properly working and operated. Such systems are required for service stations in parts of California.

Self-service dispensing of gasoline is a relatively new marketing method pioneered by independent operators on the West Coast and in the southern United States. Today, it accounts for 30% of gasoline sold. The national market-share of the major gasoline producers has decreased recently as independents and others specializing in high-volume, low-margin sales capture a larger percentage. Of the approximately 184,000 conventional service stations and tie-in gasoline operations in the United States, service stations with some self-service operations account for 39% (ADL, 1977b). Table IX-1 indicates the types of service stations offering self-service gasoline.

Table IX-1

SELF-SERVICE OPERATIONS

Outlets Offering Self-Service	Percent of U.S. Total
Total self-service	9
Split island with self-service	26
Convenience stores	4
Total outlets with self-service	39

A recent ADL report (1977b) revealed that there are 71,300 outlets with self-service gasoline. Gasoline sold for the year ending May 30, 1977, equals approximately 87.4 x 10^9 gal in the United States. Of this amount, 27.0 x 10^9 gal (31%) was dispensed at self-service pumps. The market-share of self-service stations was surveyed for four metropolitan Air Quality Control Regions (AQCR): Boston, Dallas, Denver, and Los Angeles. The market-share held by self-service operations varied from 9% in Boston to 45% in Denver (see Table IX-2). Another study by applied Urbanetics, Inc. (1976) surveyed Baltimore and Madison, Wisconsin. The

Table IX-2

GASOLINE MARKET SHARE OF SELF-SERVICE STATIONS IN FOUR AQCRs, SPRING 1977

Type of Operation	Number of Outlets	Sales Volume (10^6 gal/yr)	Market Sharing Percent
Boston AQCR			
Full-service	2,253	1,045.1	91%
Self-service (total)	100	108.6	9
Split island	8[a]		
Self-service	92		
Convenience stores	--		
Dallas AQCR			
Full-service	2,094	924.6	61
Self-service (total)	1,124	593.8	39
Split island	480[a]		
Self-service	444		
Convenience stores	200		
Denver AQCR			
Full-service	621[b]	292.1	55
Self-service (total)	656	235.7	45
Split island	310[a]		
Self-service	226		
Convenience stores	120		
Los Angeles AQCR			
Full-service	2,518	2,472.6	53
Self-service (total)	4,780	2,154.8	47
Split island	3,632[a]		
Self-service	1,022		
Convenience stores	126		

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[a] Split island operations offering full service and self-serve islands.

[b] Of these 445 are split island operations that offer full service and mini-serve (attendant-operated) islands.

Source: ADL (1977b).

results of this study are shown in Table IX-3. It appears that about 40% of the market in urban areas is accounted for by self-service operations.

Table IX-3

GASOLINE MARKET SHARE OF SELF-SERVICE STATIONS IN TWO METROPOLITAN AREAS, 1976

Type of Operation	Sales Volume (10^6 gal/yr)	Market Sharing Percent
Baltimore SMSA		
Full-service	111.5[a]	55%
Self-service (total)	90.5	45
Split island	25.5	
Self-service	65.0	
Madison SMSA		
Full service	56.0[a]	42
Self-service (total)	77.0	58
Split island	17.0	
Self-service	60.0	

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[a] Includes the sales from mini-serve (attendant-operated) stations and 50% of the sales from split islands.

Source: Applied Urbanetics, Inc. (1976).

B. Methodology and Exposures

To estimate the people exposed to benzene from this source, several assumptions were necessary. The gasoline pumped through self-service outlets is estimated at 27.0 x 10^9 gal. The annual average fuel consumption per vehicle is 736 gal (U.S. Federal Highway Administration, 1974). If it is assumed that on the average, a person who primarily uses self-service gasoline makes one trip there per week, an average fill-up amount of 14 gal is determined by dividing 736 gal/vehicle/yr by 52 wk/yr. By dividing the average fill-up into the self-service gallons pumped, we estimate trips per year to self-service operations at 1.9 x 10^9. When this number is divided by 52 trips per person per year, the people exposed to benzene from this source is estimated at 37 x 10^6. This estimate of the population exposed assumes that the individuals using self-service gasoline never obtain gasoline at full-service stations.

Battelle conducted a preliminary study (1977b) to determine the benzene exposure levels from self-service gasoline pumping. Three samples of ambient air were taken in the breathing zone of persons filling their tanks. The results, shown in Table IX-4, indicate a wide range in the benzene concentrations of the emissions. The variations seem to be related to the subject's position in relation to the tank opening and the wind direction. Because all measurements were taken on the same day and at approximately the same time, ambient temperature did not cause the variation. Basically, if the subject was downwind of the tank opening, higher levels were recorded. The time-weighted average concentration of benzene from the three samples is 245 ppb. The average length of time taken to fill up a gasoline tank is 1.7 min. Although 14 gal per fill-up is assumed, the wide range in pumping speeds does not allow a precise estimate of time required per fill-up.

Table IX-4

SAMPLING DATA FROM SELF-SERVICE GASOLINE PUMPING

Customer	Sampling Rate (mL/min)	Nozzle Time (min)	Gallons Pumped	Sample Volume (L)	Benzene Level	
					$\mu g/m^3$	ppb
1	31	2.5	14	78	115	43
2	31	1.1	8	34	324	121
3	31	1.6	9	50	1740	647

Source: Battelle (1977b).

The estimated exposure levels are based on the information contained in Table IX-4. It is recognized that these data are quite limited and highly variable. In states where vapor recovery systems are used, the estimated exposure level may be much lower. It can be estimated that approximately 37 x 10^6 persons use self-service stations. While filling their tanks once a week, they are exposed to a benzene level of 245 ppb for 1.7 minutes. Their annual exposure is estimated at 1.5 hr. (Table IX-5 summarizes this information.)

Table IX-5

ESTIMATED POPULATION EXPOSED TO BENZENE FROM SELF-SERVICE GASOLINE

Exposure Type	Exposure Time	Annual Exposure	Population Exposed to Benzene Concentrations (ppb)*	
			245.0	Total
Self-service pumping	1.7 min	1.5 hr	37,000,000	37,000,000

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*To convert to $\mu g/m^3$, multiply concentrations by 3.2; to convert annual average exposures to 8-hour worst case, multiply concentrations by 25.

Source: SRI estimates.

X ASSESSMENT OF TOTAL EXPOSURE

A. Introduction

Because benzene sources are widespread, particularly within the urban environment, the exposures of some individuals may be significantly different from those estimated in Chapters III through IX. The results presented in these previous chapters are based on the assumption that individuals living near a source spend 24 hours of each day in that location. In fact, however, many individuals travel from their place of residence to work or shop in other areas. Thus, they are exposed to varying levels of benzene concentrations throughout the day. In this chapter, a rough analysis is made to estimate total exposure to the urban population: Total exposure is the sum of an individual's exposure to all benzene sources over a designated period (e.g., a week or a year) and in varying locations; this exposure, therefore, represents a more realistic estimate of population exposure then indicated previously.

In this approach we developed several scenarios that represent typical living patterns of individuals residing in the vicinity of benzene sources. Percentages of time spent in various activities such as sleeping, shopping, commuting to work, traveling on personal business, and working were estimated by using the findings of sociological studies. Assumptions were then made about residence locales and work locations (for those that work), and about what percentage of the population falls into each of these categories. The benzene exposure settings typical for each activity were determined from dispersion modeling and atmospheric monitoring data described in Chapters III through IX. The percentage of time spect in 1 year in various activities was multiplied by the associated benzene exposure setting (ambient benzene concentration measured in ppb) and summed to determine an individual's total exposure. Note, however, that because so few data exist, this approach necessarily has limitations and is considered a first-cut analysis.

Estimates of total exposure are linked to each source category (e.g., chemical manufacturing facilities, petroleum refineries, or urban areas). Our approach assumes that those living in the vicinity of one point source, such as a coke oven, are unaffected by other benzene sources until they move out of that point source's sphere of influence. In the analysis presented in this Chapter, variations in exposure levels result from travel away from the residence by commuting to work, shopping, or traveling for personal business. Although the estimates given here improve our understanding of expected exposures to individuals in the vicinity of sources, they do not help in understanding how overlapping sources might affect individual exposures. For example, Houston, Texas, has six chemical manufacturing facilities, five petroleum refineries, and one coke oven. Without atmospheric monitoring data, it is impossible to estimate precise total exposures to individuals in that city.

This analysis thus provides a more realistic evaluation of exposures to individuals than is provided by source-specific analysis. Although many assumptions are required, the estimates used in this chapter rely as much as possible on studies of human behavior and on statistical population data. Because individuals generally spend more than 60% of the time at home under the annual average condition, short-term monitoring data have been combined with annual average estimates to estimate total exposure. Cities with highly directional wind roses or more than one large benzene source may have significantly different conditions from those estimated. In addition, it is assumed that outdoor benzene concentrations are similar to indoor concentrations. However, no indoor monitoring has been conducted to verify this assumption. Such problems will remain unresolved until much more atmospheric monitoring is conducted.

B. Determination of an Individual's Use of Time

The first step in estimating total exposure is to determine an individual's use of time. John P. Robinson of the Communication Research Center at Cleveland State University (1977) has extensively researched

Americans use of time. For his survey, he required individuals to keep time diaries of the daytime and nightime activities over a 1-month period--a technique whose basic reliability and validity had been established by several earlier methodological studies. A time diary study was conducted for the first time in 1965 and was repeated in 1975 to evaluate changes over the 10-year period. Survey results were presented in terms of the sex, employment, and marital status of those surveyed.

Because we were interested in estimating the amount of time spent away from the residence, we needed data for those employed full-time. The results for employed men shown in Table X-1 provide the best measure of that. No reliable data were available for employed women. (Part-time female workers were included in the statistics for employed women in Robinson's study, thus tending to bias the results.)

Table X-1

PERCENTAGE OF TIME SPENT PER WEEK IN MAJOR TYPES OF ACTIVITIES BY EMPLOYED MEN IN URBAN AREAS, 1975

Activity	% of Time per Week
Sleep	32%
Work for pay	26
Family care	6
Personal care	12
Leisure (total)	24
Organizations	2.5
Media	11
Social life	4.5
Recreation	2
Other leisure	4

Source: Robinson (1977).

To estimate commute time, travel time for personal business, and shopping time, the activities contained within each major activity shown in Table X-1 must be clearly understood. "Work for pay" includes all work, plus breaks, and commuting. "Family care" includes shopping, housework, child care, and helping others. "Personal care" includes all hygiene, meals, and travel associated with family and personal care. The time spent on adult education and organized activity, including religion, are part of the "organizations" category. "Media" includes radio, television, reading, and movies. "Social life" includes the time spent on entertainment, social visits, and conversation. "Recreation" includes sports, outdoor activities, and walking. The "other leisure" category includes hobbies, records, letters, resting and relaxing, and all leisure travel.

Estimates of commuting time were obtained from the Nationwide Personal Transportation Survey conducted by the Federal Highway Administration (Department of Transportation, 1973). As shown in Table X-2, commute time from home to work was reported in terms of population by place of residence. The average for incorporated localities was 21 minutes. Assuming two weeks of vacation per year, individuals spend 2% of their time per year commuting. For an upper limit, those living in incorporated areas with populations exceeding 1,000,000 spent 3% of their time commuting.

If the limitations of the available monitoring data are considered, an individual is assumed to be exposed to similar levels of benzene whether commuting to work during rush hour or driving on freeways at other times. As a result, the times estimated for each of these activities were combined into one category.

Available surveys lack specificity in regard to shopping or to driving a car for nonwork activities. Consequently, we developed best-judgment estimates of the percentages of time that could be attributed to these activities. Visits to rural areas for vacation or other leisure activities were estimated to range from 2 to 4% of time spent. The amount of time spent shopping in suburban locations or downtown areas

Table X-2

PERCENT OF THOSE EMPLOYED* BY PLACE OF RESIDENCE AND COMMUTING TIME TO WORK

Population Place of Residence	Home-to-Work Commuting Time (min)					Average for all Workers (min)
	15 & less	16-25	26-35	36 & more	All	
Unincorporated areas	50.9	19.1	13.1	16.7	100.0	23
Incorporated areas						
Less than 5,000	60.3	16.8	12.9	10.0	100.0	18
5,000 - 24,999	58.4	16.2	13.3	12.1	100.0	19
25,000 - 49,999	61.1	17.1	11.8	10.0	100.0	19
50,000 - 99,999	56.4	21.5	10.7	11.4	100.0	20
100,000 - 999,999	51.3	22.8	16.0	9.9	100.0	21
1,000,000 and above	28.5	18.5	20.5	32.5	100.00	32
All incorporated places	53.2	19.0	14.4	13.4	100.0	21
All areas and places	52.5	19.1	14.0	14.4	100.0	22

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*Does not include workers that work at home or at no fixed address.

Source: Department of Transportation, Federal Highway Administration, 1973.

was estimated at 2 to 3% and was assumed to be distributed equally between the two locations.

The results of this analysis are shown in Table X-3. Nine scenarios describe most of the possible combinations for residing and working in one of three locations: vicinity of source, suburb, or central city. Place of residence and place of work are the same if an individual works near his/her residence, goes to school, does not work, is retired, or is an invalid. Therefore, "work" can loosely be defined as daytime location.

C. Distribution Into Population Subgroups

Although the precise number of people maintaining a particular life style in the vicinity of each source or in an urban area cannot be accurately established, reasonable estimates can be made by grouping those individuals into scenarios that represent common living patterns (as shown in Table X-3). The next step toward estimating total exposures is to determine the percentage of the exposed population that can be assigned to each scenario.

A first-cut assignment is made by determining the percentage of the population that stays at or near home the majority of the time. Census data indicate that 48% of the population is likely to be in school (elementary, junior high, and high school), or retired (65 and older). The labor force distribution for 1974 shows that another 14% of the total population, that is those between the ages of 20 and 65, does not work. Therefore, roughly 60% are constantly in the vicinity of their homes. The remaining 40% of the population are assumed to work in the vicinity of their homes or to commute to other locations. The results of this analysis are shown in Table X-4. Best judgment was used to develop these percentages.

Very few quantitative data are available to estimate the commuting behavior of people. In this analysis, only 20% of those individuals residing in central cities are assumed to commute outside those areas to work. Working individuals residing in suburban areas are assumed to commute outside those areas for work. On the other hand, those living

Table X-3

ESTIMATED ANNUAL DISTRIBUTION OF
TIME SPENT IN VARIOUS ACTIVITIES AND LOCATIONS

Scenario		Percentage of Time Spent					Total % Time Spent
Reside	Work	Commute/ Freeway	Central City	Suburb	Vicinity* of Source	Rural	
Vicinity of source*	Vicinity of source	1	1	1	93	4	100%
Vicinity of source	Suburb	4	2	26	64	4	100
Vicinity of source	Central city	4	26	2	64	4	100
Suburb	Suburb	1	1	94	+	4	100
Suburb	Vicinity of source	4	3	65	24	4	100
Suburb	Central city	4	27	65	+	4	100
Central city	Central city	1	96	1	+	2	100
Central city	Vicinity of source	4	68	2	24	2	100
Central city	Suburb	4	68	26	+	2	100

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*Source indicates chemical manufacturing facilities, coke ovens, and petroleum refineries.

+Assumed to be less than 1%.

Source: SRI estimates.

Table X-4

DISTRIBUTION OF THE POPULATION INTO GROUPS AFFECTED BY OTHER BENZENE EXPOSURE SETTINGS

Scenario		% of
Reside	Work	Population
Vicinity of source	Vicinity of source	65
Vicinity of source	Suburb	10
Vicinity of source	Central city	25
Total-Source		100
Suburb	Suburb	70
Suburb	Vicinity of source	5
Suburb	Central city	25
Total-Suburb		100
Central city	Central city	80
Central city	Vicinity of source	5
Central city	Suburb	15
Total- Central city		100

Source: SRI estimates.

in the vicinity of coke ovens, chemical plants, or petroleum refineries, may already be situated in either a suburban or a central city area. Thus, in this analysis, it is assumed that they travel, shop, and/or commute to areas outside the sphere of influence of the facility. The fact that some of these facilities are in remote areas was not specifically considered in this analysis.

D. Selection of Applicable Exposure Data

Monitoring data have been collected in an attempt to characterize benzene concentrations near such locations as freeways, intersections, and central city areas. At the request of EPA, Battelle (1978b) collected atmospheric monitoring data for Columbus, Ohio, in suburbs, in central city areas, and during peak commute periods. The results of their study are shown in Table X-5. The 23-hour average for Site 1 in the central city was 3.9 ppb, whereas the daytime average was 4.4 ppb. This site was described as a midtown intersection with a high traffic load throughout normal business hours. Site 2 was located adjacent to a major commuting highway leading into the business district. Grab samples taken during peak volume traffic gave an average of 6.4 ppb. The average concentration of four 8-hour samples at Site 2 was 4.1 ppb, and the daytime average was 5.[*] Site 3 was located in a residential neighborhood approximately 1 mile from the central business district with a low service station density and no other major known stationary sources of benzene. The 24-hour average benzene concentration measured at Site 3 was 1.5 ppb.

The city of Columbus measured traffic volume at Site 2 during the atmospheric monitoring (see Table X-6). The density of traffic flow in (cars/liter sampled) appears to be correlated with the measured benzene concentrations at the monitoring site on the same side of the highway ($n = 8$, $r = 0.82$). The consistently lower density on the eastbound side

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[*] Two other 8-hour samples and three grab samples were lost at this location, thereby making these data statistically open to question.

Table X-5

RESULTS OF BATTELLE ATMOSPHERIC MONITORING STUDY

Site* No.	Trap No.	Date	Sampling Period		Barometer, mmHg	Temp, F	Wind			RH (%)	Conditions	Benzene Conc (ppb)
			Start	Finish			Direction	Speed m/s	Speed (mi/hr)			
3	54	3/15	6:45 AM	2:16 PM	29.38	34-39	150-330	1.66-2.19	(3.6-4.7)	78-61	drizzle, then	2.0
3	260	3/15	2:16 PM	9:57 PM	29.38	35-40	350-360	1.17-1.95	(2.5-4.2)	67-57	overcast	1.4
3	3	3/15	2:11 PM	9:57 PM	29.38	35-40	350-360	1.17-1.95	(2.5-4.2)	67-57	overcast	1.4
3	8	3/15-3/16	9:57 PM	8:04 AM	29.35	33-40	45-360	0.86-2.19	(1.9-4.7)	60-75	overcast	1.3
2a	95	3/15	7:43 AM	9:45 AM	29.38	33-36	150	1.66-1.87	(3.6-4.0)	78	drizzle, then	8.6
2a	143	3/15	7:43 AM	3:28 PM	29.38	33-40	150-350	1.66-2.19	(3.6-4.7)	78-61	overcast	7.5
2a	129	3/15	3:28 PM	5:54 PM	29.38	37-40	350-360	1.45-1.80	(3.1-3.9)	57-62	overcast	6.9
2a	209	3/16	6:58 AM	9:01 AM	29.35	32-33	330-360	1.40-2.19	(3.0-4.9)	77	overcast	4.8
2b	6	3/15	8:12 AM	3:42 PM	29.38	33-40	150-350	1.66-2.19	(3.6-4.7)	78-61	drizzle, then	3.4
2b	175	3/15	3:42 PM	5:59 PM	29.38	37-40	350-360	1.45-1.80	(3.1-3.9)	57-62	overcast	5.3
2b	130	3/15	3:42 PM	11:20 PM	29.38	37-40	350-360	1.00-1.95	(2.2-4.2)	57-67	overcast	3.3
2b	39	3/15-3/16	11:20 PM	9:07 AM	29.35	32-37	45-360	0.86-2.19	(1.9-4.7)	59-75	overcast	2.2
1	148	3/15	7:12 AM	2:55 PM	29.38	33-39	150-350	1.66-2.19	(3.6-4.7)	87-61	drizzle, then	5.1
1	100	3/15	3:01 PM	10:30 PM	29.38	37-40	350-360	1.00-1.95	(2.2-4.2)	57-67	overcast	5.3
1	20	3/15	2:55 PM	10:30 PM	29.38	37-40	350-360	1.00-1.95	(2.2-4.2)	57-67	overcast	2.9
1	70	3/15-3/16	10:37 PM	8:15 AM	29.35	32-40	45-360	0.86-2.19	(1.9-4.7)	59-75	overcast	2.4

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*Key

Site 1 = downtown Columbus, Ohio.
Site 2 = near downtown Columbus, Ohio; major commute route; a and b are on opposite sides of the street.
Site 3 = suburban residential Columbus, Ohio.

Source: Battelle, 1978b, draft report.

Table X-6

TRAFFIC VOLUME AND DENSITY DURING BENZENE SAMPLING PERIODS AT SITE 2

Trap No.	Date	Sampling Period		Volume of Air Sampled (ℓ)	One-Way Traffic	Total Traffic	Density (Cars/Liter sampled)		Conc of Benzene in Air (ppb)
		Start	Finish				One-Way Traffic	Total Traffic	
					Sampling Site 2a, 518 East Broad Street				
					Westbound Traffic (same side of highway as sampler)		Westbound Traffic		
95	3/15	7:43 AM	9:45 AM	3.7	3,868*	5,132*	1045	1387	8.6
143	3/15	7:43 AM	3:28 PM	10.4	10,832*	17,537*	1041	1686	7.5
129	3/15	3:28 PM	5:54 PM	4.0	3,870	8,402	968	2100	6.9
209	3/16	6:58 AM	9:04 AM	2.9	4,465	5,645	1540	1947	4.8
					Sampling Site 2b, 547 East Broad Street				
					Eastbound Traffic (same side of highway as sampler)		Eastbound Traffic		
6	3/15	8:12 AM	3:42 PM	13.8	6,799*	16,741*	493	1213	3.4
175	3/15	3:42 PM	5:59 PM	4.5	4,082	7,652	907	1700	5.3
130	3/15	3:42 PM	11:20 PM	13.8	7,231	13,625	524	987	3.3
39	3/15-3/16	11:20 PM	9:07 AM	17.7	2,194	8,352	124	472	2.2

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*Portions of this count were estimated from the following morning's count.

Source: City of Columbus, Division of Traffic Engineering, as cited in Battelle draft report (1978b).

may, to a large extent, explain why the sampling stations on that side registered lower readings.

As discussed in Chapter VIII, most of the limited atmospheric monitoring data have been collected in the vicinity of urban areas. Robinson et al. (1973) reported the results of studies measuring hydrocarbon concentrations in the nonurban atmosphere. The measurements taken in the continental United States are shown in Table X-7. They range from 0.3 to 1.1 ppb, with an average of 0.7 ppb. These results appear to be consistent with the widespread nature of benzene emissions and benzene's low atmospheric reactivity.

Radian Corporation (1978) monitored ambient benzene in Burnet, Texas, (a rural community) for Shell Oil Corporation. Three 24-hour samples were collected on consecutive days under variable meteorologic conditions. Complete quality control information was unavailable for these data. Measured benzene concentrations ranged from 3 to 4 ppb. The measurements are not consistent with others taken in remote areas. No explanation was offered for these results.

Table X-7

BENZENE CONCENTRATIONS IN REMOTE AIR
SAMPLES FROM THE CONTINENTAL UNITED STATES

State	Location	Date	Benzene Concentration (ppb)
California	Point Reyes	12/9/71	0.3
Idaho	Hells Canyon	11/6/71	
	Sample 1		0.8
	Sample 2		0.8
Idaho	Moscow Mountain	7/16/71	
	Ground		0.9
	Airborne		0.8
Vermont	Camel's Hump	9/8/71	1.1
Washington	Brethway-Gunderson	8/4/71	
	Ground		0.4
	Airborne		0.5

Source: Washington State University (1971) as cited in Robinson et al. (1973).

In the absence of adequate atmospheric monitoring data, dispersion modeling was undertaken to provide approximate estimates of benzene concentrations in the vicinity of specific locations. Chapters III through V describe dispersion modeling analysis and results for three benzene point sources. In Chapter VIII, the Hanna-Gifford dispersion equation was used to estimate average annual benzene concentrations in suburban areas (see Table VIII-5). If a background concentration of 0.5 ppb is included, the estimated concentrations ranged from 0.73 to 2.0 ppb for suburban areas in six large cities and appear to be reasonably close to the suburban values found in Battelle's atmospheric monitoring study (see Table X-5).

The highest benzene concentrations determined by dispersion modeling for a short period were estimated in the vicinity of major intersections. As shown in Table X-8, 8-hour average concentrations ranged from 12 to 28 ppb. Annual average benzene concentrations, however, are similar to those measured by Battelle along a major commuting arterial (Site 2 on Table X-5).

The selected benzene exposure settings for determining total exposure are shown in Table X-9. These estimates represent a combination of the best monitoring and modeling data available to date and our best judgment. Although limitations may be involved in using dispersion modeling data in conjunction with monitoring data, the methodology employed in this type of analysis does provide a more realistic evaluation of total exposure to an individual.

Several additional studies are worth noting. A recent study by Messer Associates, Inc., for the U.S. Department of Transportation (1977) analyzed the health effects of bicycling in an urban environment by studying 10 male subjects bicycling or driving through the streets of Washington, D.C., under systematically varied conditions. No major adverse short-term effects were noted, but the carboxyhemoglobin (COHb) levels measured for the motorist controls were slightly higher than those for the bicyclists. The authors theorized (1) that the carbon monoxide (CO) encountered in traffic slow-downs and intersection delays may have

Table X-8

BENZENE CONCENTRATIONS IN THE VICINITY OF MAJOR INTERSECTIONS BASED ON DISPERSION MODELING

City	Location*	Number of Lanes (main road x cross road)	Distance† (m)	8-Hour Average Benzene Concentration (ppb)	Average Annual Benzene Concentration (ppb)
Hartford, CT	Buckingham St. at Washington St.	4 x 4	8	28	6.9
Denver, CO	Colfax Ave. at Colorado Blvd.	6 x 8	22	37	4.7
Waltham, MA	Moody St. at Carter St.	4 x 3	24	28	6.9
Washington, DC	Wisconsin Ave. at Western Ave.	6 x 6	24	28	6.9
Peoria, IL	Rt. 150 at Scenic Dr.	8 x 5	20	22	5.3
Springfield, IL	MacArthur Blvd. at S. Grand Ave.	7 x 6	22	12	3.1
Oakbrook, IL	Rt. 83 at 22nd St.	4 x 4	20	23	5.6

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*These locations are all signalized intersections. Number of lanes includes turn lanes in all cases. Wind speed is 1 m/s.

†Distance from nearest roadway to major receptor.

Source: Schewe (1977) using the Hot Spot Guideline.

Table X-9

BENZENE EXPOSURE SETTINGS IN VICINITY OF SPECIFIC LOCATIONS

Location	Average Benzene Concentrations (ppb)	Averaging Time (hr)	References
Major intersections	12 - 28	8	Dispersion modeling: Schewe, 1977 (Table X-8).
Freeway/peak commute	6 - 7	2 - 3	Monitoring data: Battelle, 1978 (Table X-5).
Central city	3 - 4	24	Monitoring data: Battelle, 1978b (Table X-5).
Suburb	1 - 2	24-Annual	Monitoring data: Battelle, 1978b (Table X-5). Dispersion modeling: SRI (Chapter VIII).
Source*	Varies by source	Annual	Dispersion modeling: SRI (Chapters III, IV, V).
Rural	ND - 1.0	0.5 - 1	Monitoring data: Robinson et al., 1973 (Table X-7).

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*"Source" means chemical manufacturing facilities, coke ovens, and petroleum refineries.

ND = non-detectable

more impact on increasing levels of COHb than the low levels of CO encountered by moving bicyclists and motorists while traveling through the study area, and (2) that motorists may be exposed to higher CO levels than bicyclists who have more mobility in heavy traffic. An additional finding indicates that CO levels monitored at the study's permanent air monitoring station were consistently lower than the CO levels encountered by bicyclists and motorists in the study.

Another study conducted by Chaney of the University of Michigan (1977) monitored CO concentrations inside a traveling car. Some of the more important findings were (1) peaks in concentration are primarily the result of traffic slowing down as a result of congestion; (2) CO concentration varied from 2 to 50 ppm, depending primarily on the number of stationary or accelerating vehicles close to the monitored vehicle; (3) measurements on 760 vehicles showed a wide variation in CO concentrations ranging from 0.05 ppm to 45 ppm; and (4) a large proportion of the vehicles monitored produced only a small amount of the total CO, whereas a relatively small number of the total vehicles contributed almost half of the total monitored CO.

The results of these two studies indicate the concentrations to which motorists are exposed from automotive-related emissions, including benzene, are higher than measured at permanent atmospheric monitoring stations. Therefore, the use of monitoring data to represent short-term peak exposures from traffic flow may significantly underestimate actual exposures for motorists.

E. Summary of Exposures

The estimates for total exposure were calculated by the following steps:

1. Determine the number of people within each scenario and for each source by multiplying the exposed population (Table I-1) by the percentages shown in Table X-4. Urban population is broken down into suburban and central city subgroups by assuming that the population exposed to the higher range in

Table I-1 is located in central cities. The population residing near service stations is exposed to higher overall benzene levels (additive to the estimated urban exposure from automobile emissions).

2. Multiply the percentage of time spent shown in Table X-3 by the mid-range of the applicable benzene exposure settings shown in Table X-9. Sum the values for each scenario. This represents the total exposure in ppb for an individual within each scenario. Table X-10 shows the calculated values for each of the scenarios.

3. Determine ppb-person-years by multiplying the total exposure levels by the number of exposed individuals and by summing the results. Example calculations for two benzene sources are shown in Table X-11.

The total exposure to individuals living in the vicinity of benzene sources is shown in Table X-12. In comparing this table with Table I-1, several important differences are evident. Urban exposures, for example, now include automobile emissions and gasoline service stations. The other significant change is the redistribution of the people exposed within the first two ranges of benzene concentrations. The exposure of more than 90% of the people in the lowest range has increased sufficiently to put them into into the second range. The largest change occurred in the urban exposures category and results from summing the exposures from automobile emissions and gasoline service stations. In addition, approximately 37 million people are estimated to use self-service gasoline stations and are estimated to be exposed to 245 ppb at each trip with an annual exposure time of 1.5 hr/yr.

This analysis shows that lifestyle patterns affect annual average benzene exposures and that generally the effect is to increase those exposures. This approach appears to be better than a source-specific analysis alone because it combines several urban exposures into one estimate of annual exposure. The current state of the social sciences does not allow a more sophisticated estimate of time spent in certain activities or the number of people conforming to certain living patterns. Nevertheless, a rough approximation of those uncertainties affords a reasonable evaluation of total exposure to individuals residing in the vicinity of sources of atmospheric benzene.

Table X-10

ESTIMATE OF TOTAL EXPOSURE FOR EACH SCENARIO

Scenario[*]		Median Total Exposure (ppb)[†]	
Reside	Work	Residential	Mixed Activity
Vicinity of source (0.1-1.0)	Vicinity of source (0.1-1.0)	0.5	0.6
Vicinity of source (1-4)	Vicinity of source (1-4)	2.5	2.5
Vicinity of source (4-10)	Vicinity of source (4-10)	7.0	6.6
Vicinity of source (> 10)	Vicinity of source (> 10)	20	19
Vicinity of source (0.1-1.0)	Suburb	0.5	1.1
Vicinity of source (1-4)	Suburb	2.5	2.3
Vicinity of source (4-10)	Suburb	7.0	5.2
Vicinity of source (> 10)	Suburb	20	14
Vicinity of source (0.1-1.0)	Central city	0.5	1.5
Vicinity of source (1-4)	Central city	2.5	2.8
Vicinity of source (4-10)	Central city	7.0	5.7
Vicinity of source (> 10)	Central city	20	14
Suburb	Suburb	1.0	1.1
Suburb	Vicinity of source[‡]	1.0	1.3
Suburb	Central city	1.0	1.9

Table X-10 (concluded)

Scenario[*]		Median Total Exposure (ppb)[†]	
Reside	Work	Residential	Mixed Activity
Central city	Central city	3.5	3.5
Central city	Vicinity of source[‡]	3.5	3.9
Central city	Suburb	3.5	3.0

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[*] Because annual average exposure varies in the vicinity of a source, a separate estimate is made for each range of benzene exposures as shown in parenthesis after applicable scenarios. Source is used to mean chemical manufacturing facilities, coke ovens, and petroleum refineries.

[†] Median total exposure is the mid-point of the benzene ranges. Residential exposures are the estimates shown in Table I-1 and imply that 24 hours of each day are spent in the vicinity of the source. Mixed activity total exposure is the median exposure assuming that some time is spent in other benzene exposure settings.

[‡] A population-weighted exposure of 1.2 ppb was estimated and used to characterize levels in the vicinity of sources.

Source: SRI estimates.

Table X-11

EXAMPLE CALCULATION OF TOTAL EXPOSURE
FOR TWO BENZENE SOURCE CATEGORIES

Reside	Work	% of Population	Estimated Exposure Level (ppb)	Exposed Population (10^6)	Comparison Among Sources (10^6 ppb-person-yr)
Petroleum Refineries					
Benzene Concentration Range = 0.1-1.0 ppb					
Vicinity of source	Vicinity of source	65	0.6	3.25	2.0
Vicinity of source	Suburb	10	1.1	0.5	0.6
Vicnity of source	Central city	25	1.5	1.25	1.9
Benzene Concentration Range = 1.1-4.0 ppb					
Vicinity of source	Vicinity of source	65	2.5	0.002	0.005
Vicinity of source	Suburb	10	2.3	0.0003	0.0007
Vicinity of source	Central city	25	2.8	0.00075	0.002
Total - Petroleum Refineries*				5.0	4.5
Urban-Central City					
Benzene Concentration Range = 1.1-4.0 ppb					
Central city	Central city	80	3.5	36	126.0
Central city	Vicinity of source	5	3.9	2	7.8
Central city	Suburb	15	3.0	7	21.0
Subtotal - Central city				45	154.8

Table X-11 (concluded)

Reside	Work	% of Population	Estimated Exposure Level (ppb)	Exposed Population (10^6)	Comparison Among Sources (10^6 ppb-person-yr)
Urban-Suburban Locations					
Benzene Concentration Range = 0.1-1.0 ppb					
Suburb	Suburb	70	1.1	48	52.8
Suburb	Vicinity of source	5	1.3	4	5.2
Suburb	Central city	25	1.9	17	32.3
Subtotal - Suburban				69	90.3
Total - Urban exposures*				110	250.0

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*Rounded to two significant figures.

Source: SRI estimates.

Table X-12

SUMMARY OF ESTIMATED TOTAL EXPOSURES[*] OF PEOPLE RESIDING IN THE VICINITY OF ATMOSPHERIC BENZENE SOURCES

Vicinity of Residence	Number of People Exposed					Comparison Among Sources†‡
	Annual Average Benzene Concentrations (ppb)				Total†	(10^6 ppb-person-year)
	0.1-1.0	1.1-4.0	4.1-10.0	> 10.0		
Chemical manufacturing	3,900,000	3,100,000	200,000	80,000	7,300,000	10.0
Coke ovens	200,000	100,000			300,000	0.2
Petroleum refineries	3,250,000	1,750,000			5,000,000	4.5
Urban areas		110,000,000			110,000,000	250.0

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[*] The term "total exposures" is used to mean the sum of an individual's exposure to atmospheric benzene from a variety of activities during a year. This assumes that people spend part of their time away from their residence, resulting in exposures to different benzene concentrations depending on their activity (i.e., commuting to work, shopping, traveling on personal business). Nonurban exposures are not included in this analysis but are expected to range from undetectable to 1.0 ppb.

[†] Rounded to two significant figures.

[‡] The median values shown in Table X-10 were used for this calculation instead of the mid-point of the ranges. This allows a better comparison with Table I-1.

Source: SRI estimates.

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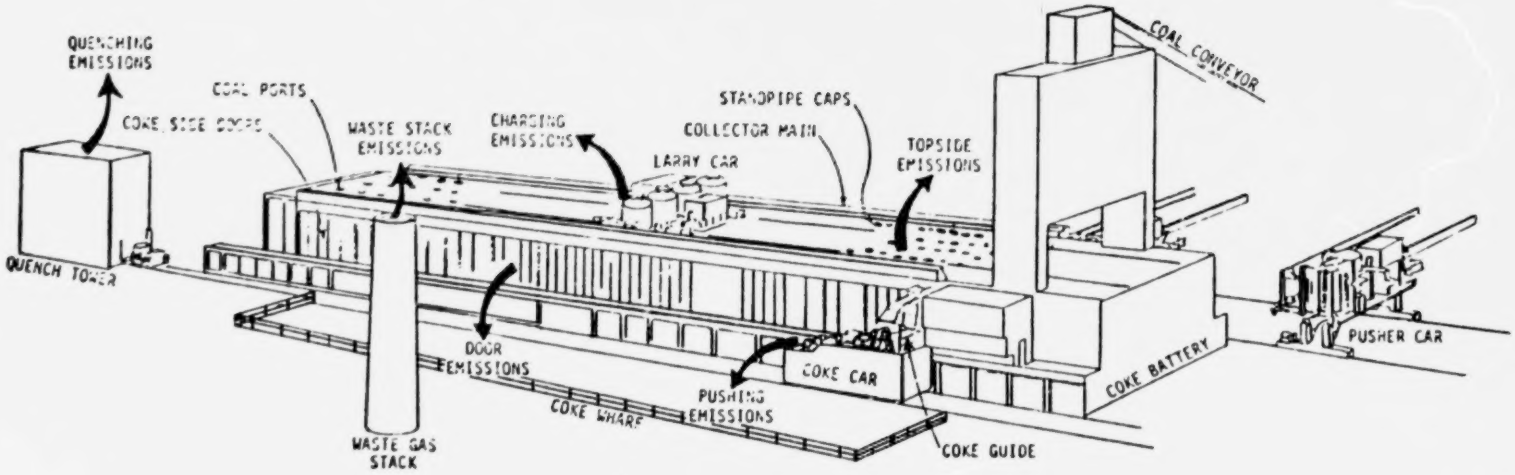
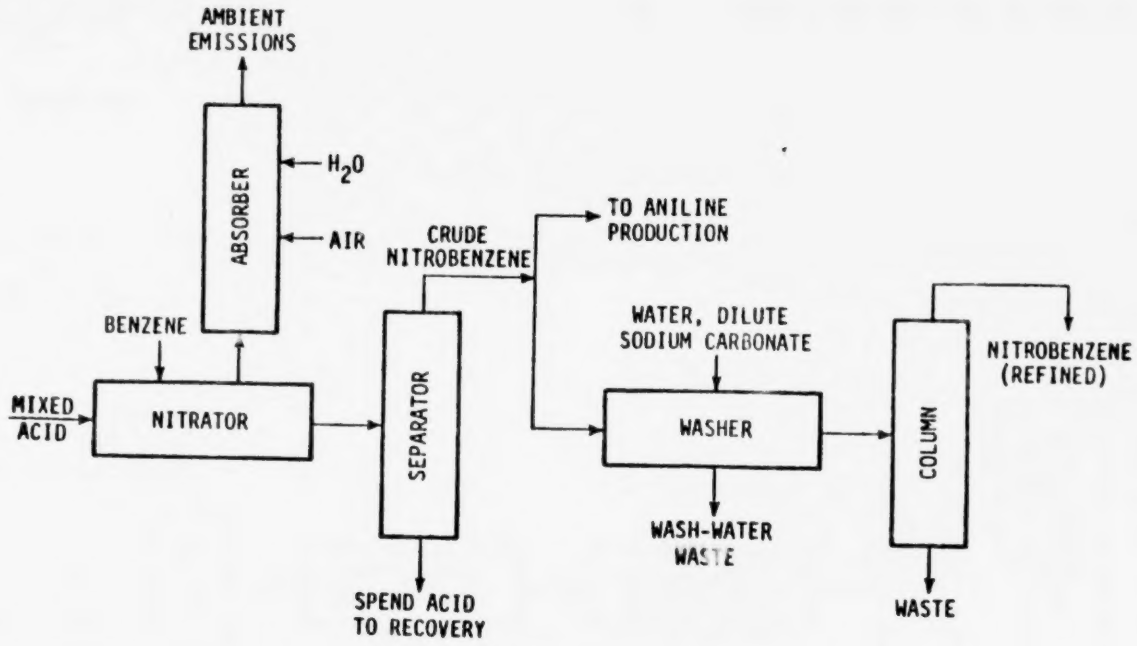
APPENDIX A

DIAGRAMS OF VARIOUS BENZENE-RELATED OPERATIONS


QUENCHING EMISSIONS
COAL PORTS
COKE SIDE DOORS
WASTE STACK EMISSIONS
CHARGING EMISSIONS
STANDPIPE CAPS
COLLECTOR MAIN
LARRY CAR
TOPSIDE EMISSIONS
COAL CONVEYOR
QUENCH TOWER
DOOR EMISSIONS
COKE WHARF
PUSHING EMISSIONS
COKE CAR
COKE GUIDE
COKE BATTERY
PUSHER CAR
WASTE GAS STACK

Source: PEDCo, 1977

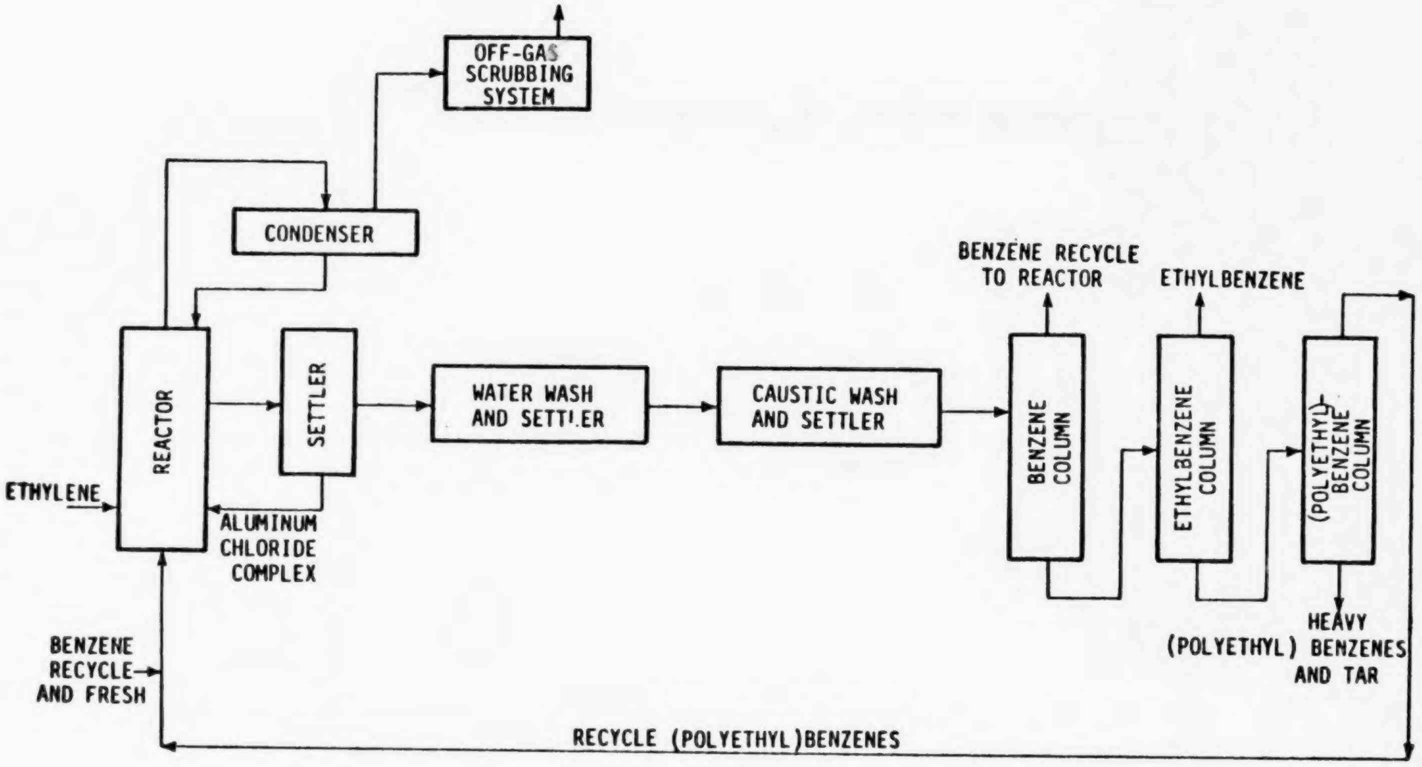
FIGURE A-1. SCHEMATIC DIAGRAM OF BY-PRODUCT COKE OVEN SHOWING POSSIBLE ATMOSPHERIC EMISSION SOURCES FOR BENZENE


AMBIENT EMISSIONS
ABSORBER
H_2O
AIR
BENZENE
MIXED ACID
NITRATOR
SEPARATOR
SPEND ACID TO RECOVERY
CRUDE NITROBENZENE
TO ANILINE PRODUCTION
WATER, DILUTE SODIUM CARBONATE
WASHER
WASH-WATER WASTE
COLUMN
NITROBENZENE (REFINED)
WASTE

$$C_6H_6 + HNO_3 \xrightarrow{H_2SO_4} C_6H_5NO_2 + H_2O$$

Source: PEDCo, 1977

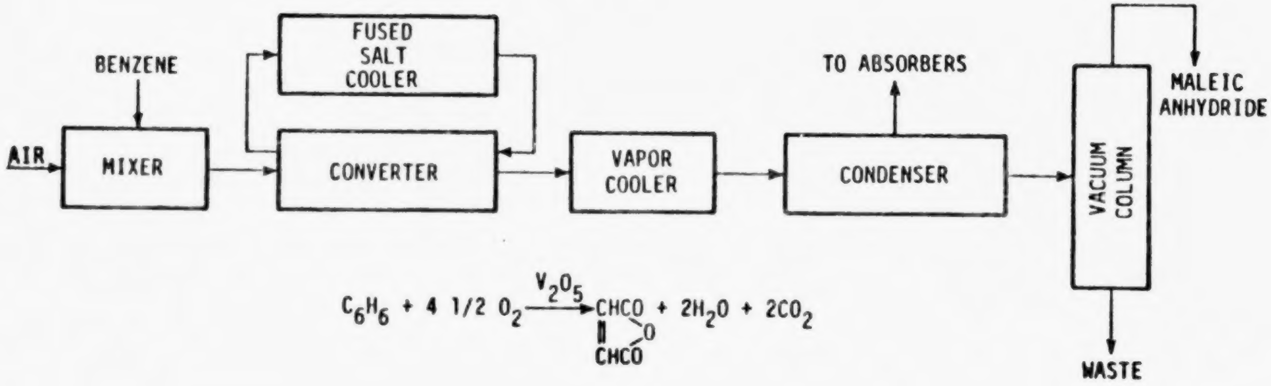
FIGURE A-2. FLOW CHART FOR NITROBENZENE MANUFACTURE FROM BENZENE AND NITRIC ACID


OFF-GAS SCRUBBING SYSTEM
CONDENSER
REACTOR
SETTLER
WATER WASH AND SETTLER
CAUSTIC WASH AND SETTLER
BENZENE COLUMN
ETHYLBENZENE COLUMN
(POLYETHYL)-BENZENE COLUMN
BENZENE RECYCLE TO REACTOR
ETHYLBENZENE
HEAVY (POLYETHYL) BENZENES AND TAR
ETHYLENE
ALUMINUM CHLORIDE COMPLEX
BENZENE RECYCLE AND FRESH
RECYCLE (POLYETHYL)BENZENES

$$C_6H_6 + C_2H_4 \xrightarrow{AlCl_3} C_6H_5C_2H_5$$

Source: PEDCo, 1977

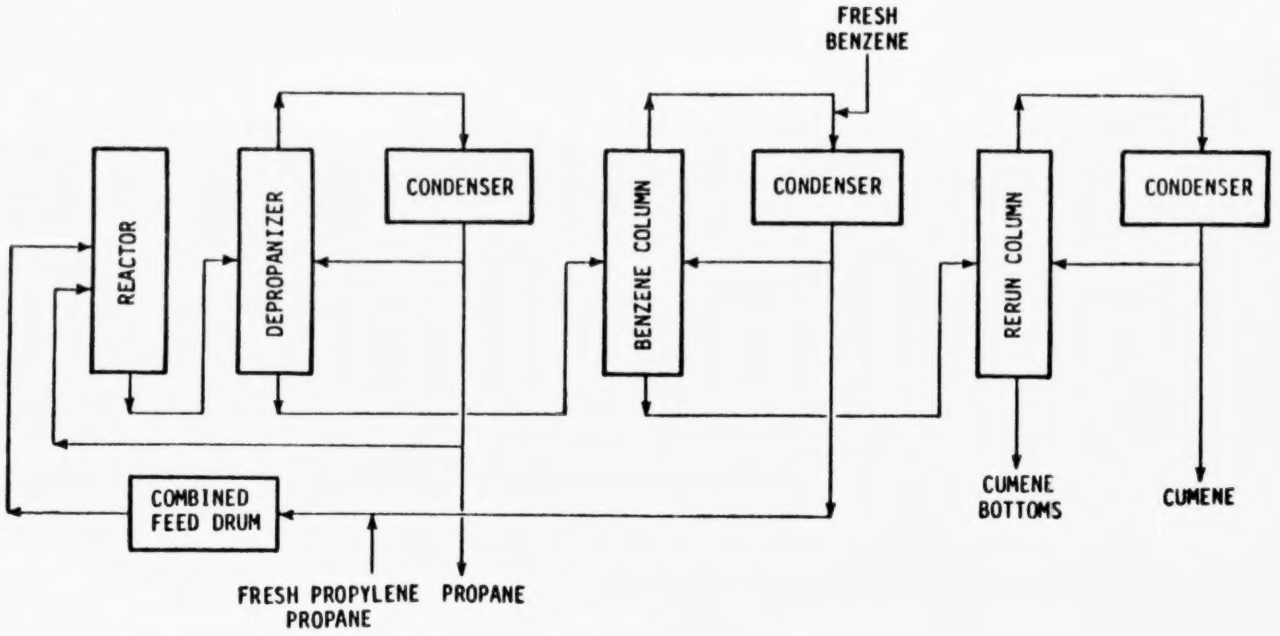
FIGURE A-3. FLOW CHART FOR ETHYLBENZENE MANUFACTURE FROM BENZENE AND ETHYLENE


AIR
BENZENE
MIXER
FUSED
SALT
COOLER
CONVERTER
VAPOR
COOLER
TO ABSORBERS
CONDENSER
VACUUM
COLUMN
MALEIC
ANHYDRIDE
WASTE

$$C_6H_6 + 4\ 1/2\ O_2 \xrightarrow{V_2O_5} \begin{matrix} CHCO \\ \| \quad \rangle O \\ CHCO \end{matrix} + 2H_2O + 2CO_2$$

Source: PEDCo, 1977

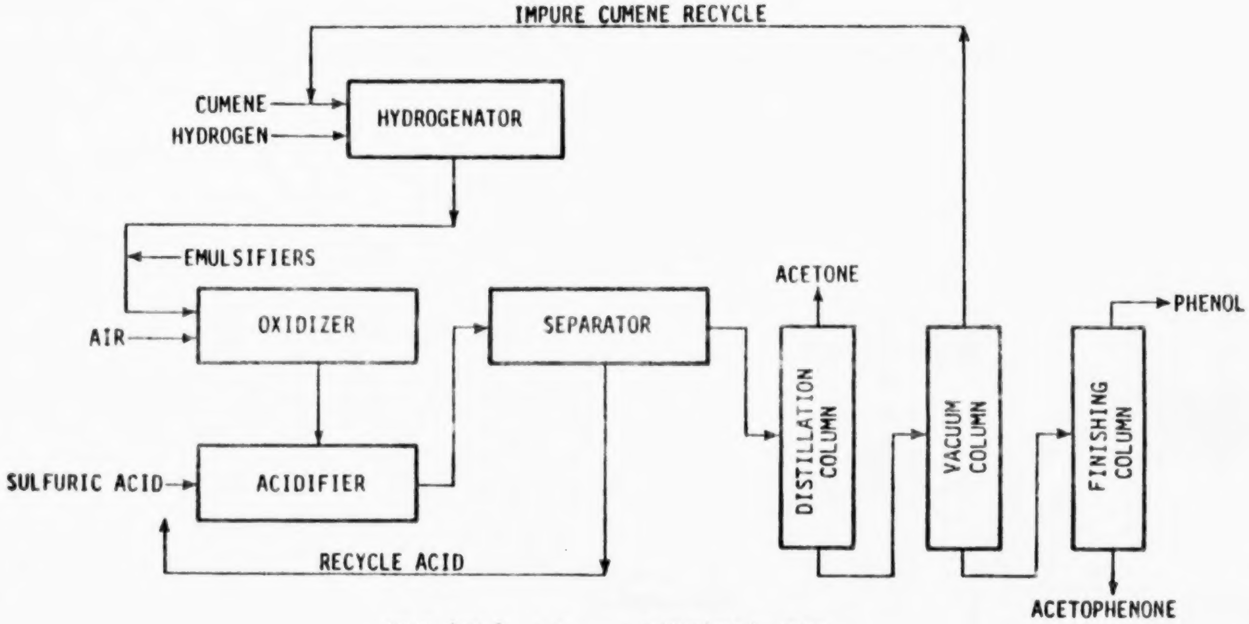
FIGURE A-4. FLOW CHART FOR THE MANUFACTURE OF MALEIC ANHYDRIDE BY CATALYTIC VAPOR-PHASE OXIDATION OF BENZENE


FRESH BENZENE
REACTOR
DEPROPANIZER
CONDENSER
BENZENE COLUMN
CONDENSER
RERUN COLUMN
CONDENSER
COMBINED FEED DRUM
FRESH PROPYLENE PROPANE
PROPANE
CUMENE BOTTOMS
CUMENE

$$C_6H_6 + CH_3CH = CH_2 \xrightarrow[\text{SOLID}]{\text{PHOSPHORIC ACID}} C_6H_5CH(CH_3)_2$$

Source: PEDCo, 1977

FIGURE A-5. PROCESS FOR THE MANUFACTURE OF CUMENE

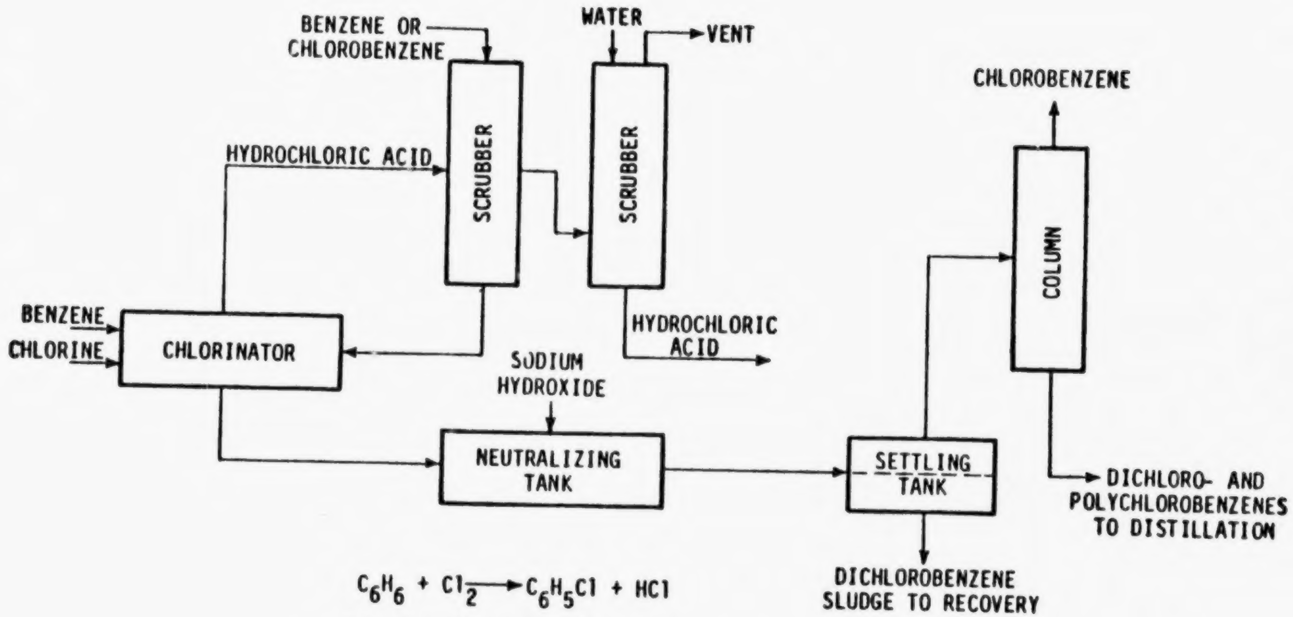

IMPURE CUMENE RECYCLE
CUMENE
HYDROGEN
HYDROGENATOR
EMULSIFIERS
AIR
OXIDIZER
SEPARATOR
ACETONE
SULFURIC ACID
ACIDIFIER
RECYCLE ACID
DISTILLATION COLUMN
VACUUM COLUMN
FINISHING COLUMN
PHENOL
ACETOPHENONE

$$CH_6H_5(CH_3)_2 + O_2 \longrightarrow C_6H_5C(CH_3)_2\ OOH$$

$$C_6H_5C(CH_3)_2\ OOH \longrightarrow C_6H_5OH + (CH_3)_2\ CO$$

Source: PEDCo, 1977

FIGURE A-6. FLOW DIAGRAM FOR THE MANUFACTURE OF PHENOL BY THE CUMENE PEROXIDATION PROCESS

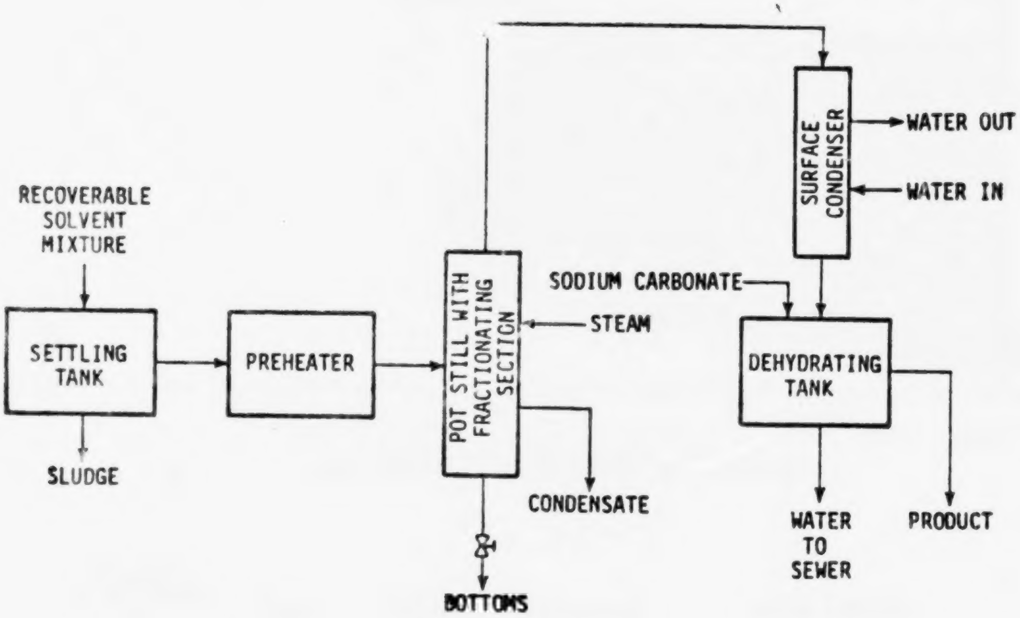

BENZENE OR CHLOROBENZENE
WATER
VENT
CHLOROBENZENE
HYDROCHLORIC ACID
SCRUBBER
SCRUBBER
COLUMN
BENZENE
CHLORINE
CHLORINATOR
HYDROCHLORIC ACID
SODIUM HYDROXIDE
NEUTRALIZING TANK
SETTLING TANK
DICHLORO- AND POLYCHLOROBENZENES TO DISTILLATION
DICHLOROBENZENE SLUDGE TO RECOVERY

$$C_6H_6 + Cl_2 \longrightarrow C_6H_5Cl + HCl$$

$$C_6H_5Cl + Cl_2 \longrightarrow C_6H_4Cl_2 + HCl$$

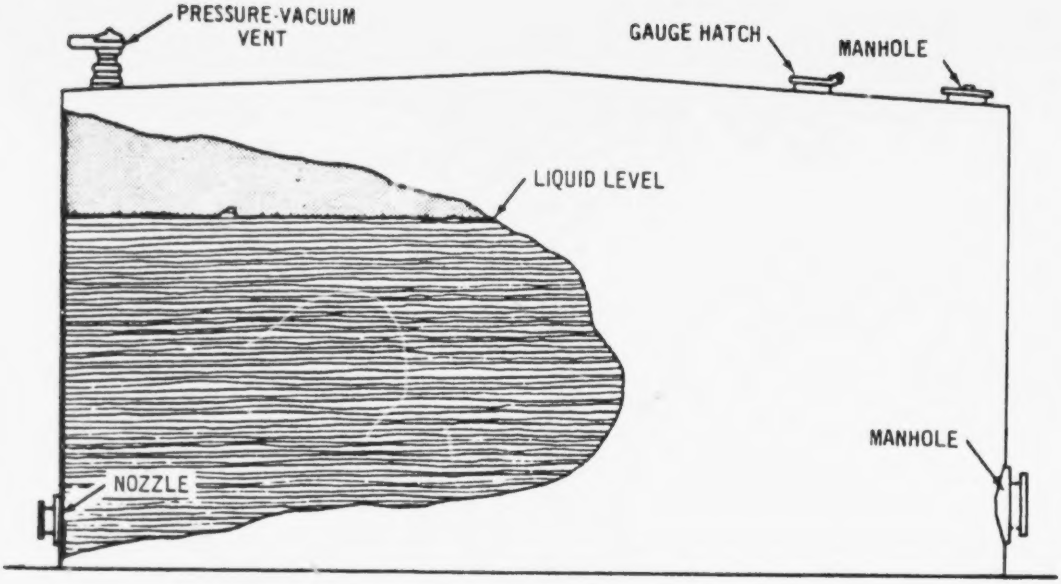
Source: PEDCo, 1977

FIGURE A-7. FLOW DIAGRAM FOR THE MANUFACTURE OF CHLOROBENZENE AND BY-PRODUCT DICHLOROBENZENES


RECOVERABLE SOLVENT MIXTURE
SETTLING TANK
SLUDGE
PREHEATER
POT STILL WITH FRACTIONATING SECTION
STEAM
CONDENSATE
BOTTOMS
SURFACE CONDENSER
WATER OUT
WATER IN
SODIUM CARBONATE
DEHYDRATING TANK
WATER TO SEWER
PRODUCT

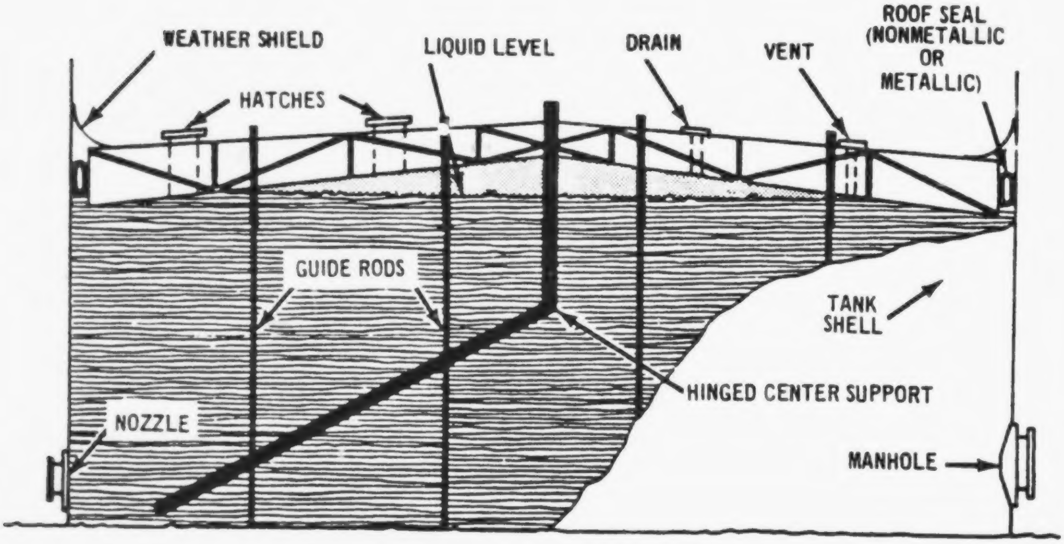
Source: PEDCo, 1977

FIGURE A-8. TYPICAL SOLVENT RE-REFINING INSTALLATION


PRESSURE-VACUUM VENT
GAUGE HATCH
MANHOLE
LIQUID LEVEL
MANHOLE
NOZZLE

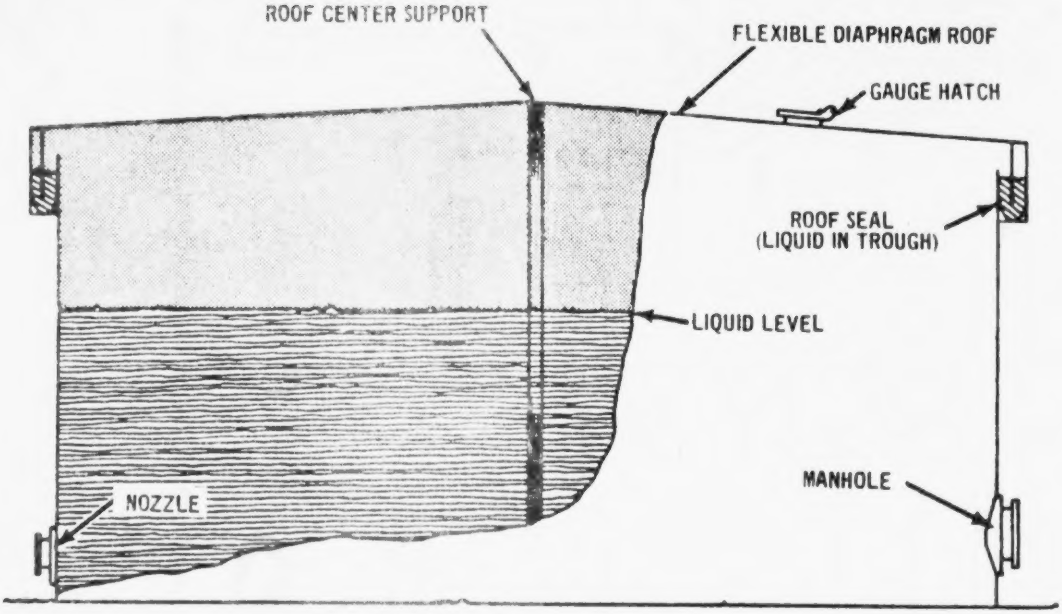
Source: PEDCo, 1977

FIGURE A-9. FIXED-ROOF STORAGE TANK


WEATHER SHIELD
HATCHES
LIQUID LEVEL
DRAIN
VENT
ROOF SEAL (NONMETALLIC OR METALLIC)
GUIDE RODS
TANK SHELL
HINGED CENTER SUPPORT
NOZZLE
MANHOLE

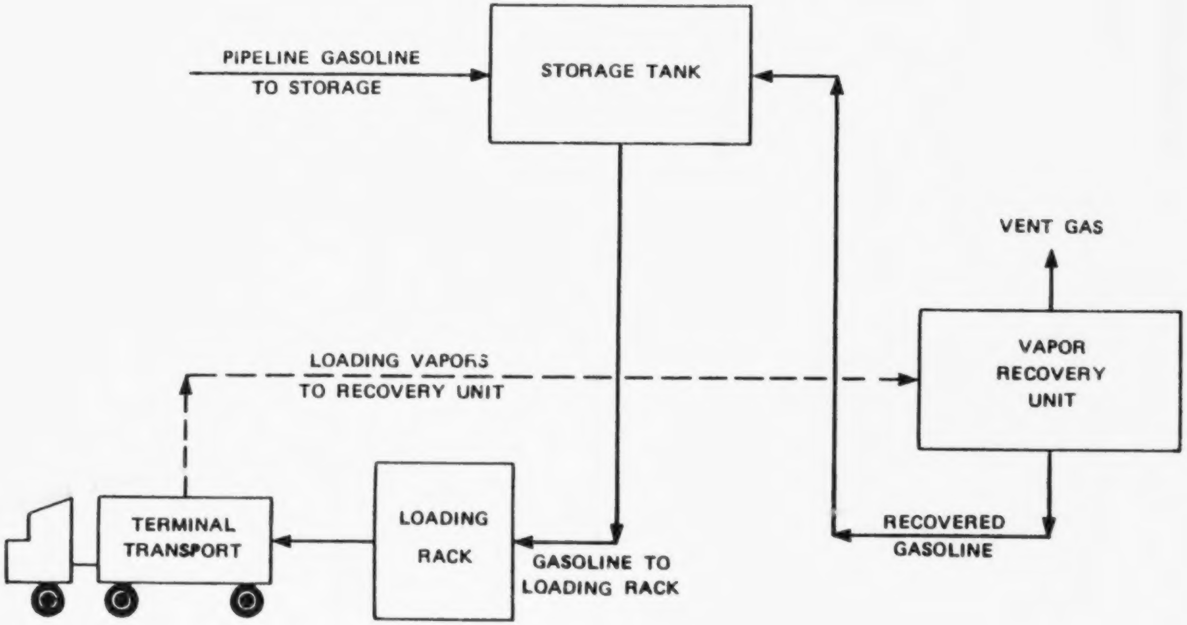
Source: PEDCo, 1977

FIGURE A-10. DOUBLE-DECK FLOATING-ROOF STORAGE TANK
(Nonmetallic Seal)


ROOF CENTER SUPPORT
FLEXIBLE DIAPHRAGM ROOF
GAUGE HATCH
ROOF SEAL
(LIQUID IN TROUGH)
LIQUID LEVEL
MANHOLE
NOZZLE

Source: PEDCo, 1977

FIGURE A-11. VARIABLE VAPOR SPACE STORAGE TANK
(Wet-Seal Lifter Type)


PIPELINE GASOLINE
TO STORAGE
STORAGE TANK
VENT GAS
VAPOR
RECOVERY
UNIT
LOADING VAPORS
TO RECOVERY UNIT
TERMINAL
TRANSPORT
LOADING
RACK
GASOLINE TO
LOADING RACK
RECOVERED
GASOLINE

SOURCE: PEDCo, 1977

FIGURE A-12. VAPOR AND LIQUID FLOW IN A TYPICAL BULK TERMINAL (Floating-Roof Tank)

APPENDIX B

EMISSION RATES AND POPULATION EXPOSURES FROM CHEMICAL MANUFACTURING FACILITIES

Table B-1

EMISSION RATES FROM DIFFERENT CHEMICALS IN EACH PLANT USING BENZENE *

ESTIMATED EMISSION RATE, JANUARY 1, 1976 (millions of kg per year)

STATE	LOCATION	COMPANY	NITRO-BENZENE	ANILINE	ETHYL BENZENE	STYRENE	MALEIC ANHYDRIDE	CUMENE	PHENOL	MONO-CHLORO-BENZENE	DICHLORO-BENZENE (O- and P-)	CYCLO HEXANE	DETERGENT ALKYLATE (Linear and Branch)	TOTAL EMISSION RATE
ALABAMA	TUSCALOOSA	REICHHOLD CHEM., INC.							0.068					0.068
CALIFORNIA	CARSON	WITCO CHEM.											0.056	0.056
	EL SEGUNDO	STD. OIL CO. OF CALIF.						0.011						0.011
	IRWINDALE	SPECIALTY ORGANICS, INC.									0.080			0.080
	RICHMOND	STD. OIL CO. OF CALIF.							0.025				0.220	0.245
	SANTA FE SPRINGS	FERRO CORP.												
DELAWARE	DELAWARE CITY	STD. CHLORINE CHEM CO., INC.								0.119	0.232			0.351
GEORGIA	CARTERSVILLE	CHEM. PRODUCTS CORP.									0.086			0.086
ILLINOIS	BLUE ISLAND	CLARK OIL & REFINING						0.012	0.040					0.052
	CICERO	KOPPERS CO., INC.					0.483							0.483
	MORRIS	REICHHOLD CHEM., INC.					2.610							2.610
	SAUGET	MONSANTO	0.031							0.182	0.111			0.324
KANSAS	EL DORADO	SKELLY OIL CO.						0.015	0.043					0.058
KENTUCKY	ASHLAND	ASHLAND OIL, INC.						0.040						0.040
LOUISIANA	BATON ROUGE	FOSTER GRANT CO.			0.272	0.558								0.830
	CARVILLE	COS-MAR, INC.			0.202	0.409								0.611
	CHALMETTE	TENNECO, INC.			0.070									0.070
	GEISMAR	RUBICON CHEM., INC.	0.238											0.238
	PLAQUEMINE	GEORGIA PACIFIC CORP.							0.120					0.120
	WELCOME	GULF OIL CORP.			0.155	0.357								0.512
MARYLAND	BALTIMORE	CONTINENTAL OIL CO.											0.215	0.215
MASSACHUSETTS	MALDEN	SOLVENT CHEM. CO., INC.									0.008			0.008
MICHIGAN	MIDLAND	DOW CHEMICAL			0.155	0.273		0.001	0.018	0.476	0.249			1.172
MISSISSIPPI	PASCAGOULA	FIRST MISSISSIPPI CORP.	0.427											0.427
MISSOURI	ST. LOUIS	MONSANTO					4.641							4.641
NEVADA	HENDERSON	MONTROSE CHEM. CORP. OF CAL.								0.112				0.112
NEW JERSEY	BOUND BROOK	AMERICAN CYANAMID	0.266											0.266
	BOUND BROOK	UNION CARBIDE							0.068					0.068
	ELIZABETH	REICHHOLD CHEM., INC.					1.353							1.353
	FORDS	TENNECO, INC.					1.180							1.180
	GIBBSTOWN	E. I. du PONT	0.637											0.637
	KEARNY	STD. CHLORINE CHEM. CO.									0.060			0.060
	WESTVILLE	TEXACO, INC.						0.029						0.029

Table B-1 (Continued)

STATE	LOCATION	COMPANY	NITRO BENZENE	ANILINE	ETHYL BENZENE	STYRENE	MALEIC ANHYDRIDE	CUMENE	PHENOL	MONO-CHLORO BENZENE	DICHLORO-BENZENE (O- and P-)	CYCLO-HEXANE	DETERGENT ALKYLATE (Linear and Branch)	TOTAL EMISSION RATE
NEW YORK	NIAGARA FALLS	ICC INDUSTRIES, INC.												
	NIAGARA FALLS	OCCIDENTAL PETROLEUM								0.024				0.024
	NIAGARA FALLS	SOLVENT CHEM. CO.									0.077			0.070
	SYRACUSE	ALLIED CHEM. CORP								0.038	0.077			0.115
OHIO	HAVERHILL	UNITED STATES STEEL							0.080					0.080
PENNSYLVANIA	BEAVER VALLEY	ARCO/POLYMERS, INC.				0.300								0.300
	BRIDGEVILLE	KOPPERS CO., INC.					1.450							1.450
	CLAIRTON	UNITED STATES STEEL												
	FRANKFORD	ALLIED CHEMICAL CORP.							0.250					0.250
	NEVILLE ISLAND	UNITED STATES STEEL					1.740							1.740
	PHILADELPHIA	GULF OIL CORP.						0.051				0.274		0.325
PUERTO RICO	GUAYAMA	PHILLIPS PETROLEUM										0.585		0.585
	PENUELAS	COMMONWEALTH OIL			0.046							0.330		0.376
	PENUELAS	UNION CARBIDE CORP						0.072	0.090					0.162
TEXAS	BAYTOWN	EXXON CORP										0.330		0.330
	BEAUMONT	E. I. du PONT	0.987											0.987
	BEAUMONT	UNION OIL CO. OF CALIFORNIA										0.280		0.280
	BIG SPRING	AMERICAN PETROFINA			0.012	0.060						0.098		0.170
	BORGER	PHILLIPS PETROLEUM										0.330		0.330
	CHOCOLATE BAYOU	MONSANTO						0.073	0.227				0.224	0.524
	CORPUS CHRISTI	COASTAL STATES GAS						0.016						0.016
	CORPUS CHRISTI	SUN OIL CO.			0.026	0.054		0.028						0.108
	CORPUS CHRISTI	UNION PACIFIC CORP										0.182		0.182
	FREEPORT	DOW CHEMICAL			0.525	1.009								1.534
	HOUSTON	ARCO/POLYMERS, INC.			0.027	0.067								0.094
	HOUSTON	THE CHARTER CO.			0.009									0.009
	HOUSTON	JOE OIL, INC.												
	HOUSTON	THE MERICHEM CO.												
	HOUSTON	PETRO-TEX CHEM CORP.					2.224							2.224
	ODESSA	EL PASO NATURAL GAS			0.077	0.102								0.179
	OYSTER CREEK	DOW CHEMICAL							0.182					0.182
	PHILLIPS	PHILLIPS PETROLEUM CO.												
	PORT ARTHUR	ARCO/POLYMERS, INC.			0.124									0.124
	PORT ARTHUR	GULF OIL CORP						0.061						0.061
	PORT ARTHUR	TEXACO										0.050		0.050
	SEADRIFT	UNION CARBIDE CORP			0.096	0.204								0.300
	SWEENEY	PHILLIPS PETROLEUM CO.										0.703		0.703

Table B-1 (Concluded)

STATE	LOCATION	COMPANY	NITROGEN	ANILINE	ETHYL BENZENE	STYRENE	MALEIC ANHYDRIDE*	CUMNE	PHENOL	MONO-CHLORO-BENZENE	DICHLORO-BENZENE (O- and P-)	CYCLO-HEXANE	DETERGENT ALKYLATE (Linear and Branch)	TOTAL EMISSION RATE
TEXAS	TEXAS CITY	MARATHON OIL CO.						0.021						0.021
	TEXAS CITY	MONSANTO			0.899	0.885								1.784
	TEXAS CITY	STANDARD OIL (INDIANA)			0.266	0.573		0.007						0.846
WEST VIRGINIA	CHARLESTON	UNION CARBIDE CORP											0.149	0.149
	FOLLANSBEE	KOPPERS CO., INC.												
	MOUNDSVILLE	ALLIED CHEM CORP	0.175				0.261							0.436
	NATRIUM	PPG INDUSTRIES, INC.								0.143	0.197			0.340
	NEW MARTINSVILLE	MOBAY CHEM CORP.	0.427											0.427
	WILLOW ISLAND	AMERICAN CYANAMIDE	0.189											0.189
WASHINGTON	ANACORTES	STIMSON LUMBER CO.							N.A.					
	KALAMA	KALAMA CHEMICAL							0.025					0.025

N.A. - NOT AVAILABLE

* SOURCE SRI ESTIMATES

Table B-2

ESTIMATED POPULATION EXPOSED TO BENZENE
FROM CHEMICAL MANUFACTURING FACILITIES, BY FACILITY

State	Location	Company	Total Benzene Emission Rate 10^6 Kg/yr	Population Exposed to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	> 10.0
Alabama	Tuscaloosa	Reichhold Chemical	0.068	20,000	500	–	–
California	Carson	Witco Chemical	0.055	30,000	400	–	–
	El Segundo	Standard Oil of Calif.	0.011	400	–	–	–
	Irwindale	Specialty Organics	0.008	200	–	–	–
	Richmond	Standard Oil of Calif.	0.245	80,000	4,000	400	–
	Santa Fe Springs	Ferro Corporation	N.A.				
Delaware	Delaware City	Standard Chlorine Chem.	0.351	20,000	1,500	200	–
Georgia	Cartersville	Chemical Products Corp.	0.086	7,000	200	–	–
Illinois	Blue Island	Clark Oil & Refining	0.052	4,000	50	–	–
	Cicero	Koppers Company	0.483	20,000	60,000	7,000	700
	Morris	Reichold Chemical	2.610	90,000	12,000	4,000	1,000
	Sauget	Monsanto	0.324	70,000	14,000	2,000	–
Kansas	El Dorado	Skelly Oil Company	0.058	4,000	80	–	–
Kentucky	Ashland	Ashland Oil	0.040	20,000	–	–	–
Louisiana	Baton Rouge	Foster Grant Company	0.830	100,000	40,000	5,000	1,000
	Carville	Cos-Mar	0.611	10,000	700	500	90
	Chalmette	Tenneco	0.07	5,000	100	–	–
	Geismar	Rubicon Chemical	0.238	4,000	100	–	–
	Plaquemine	Georgia Pacific Corp.	0.120	8,000	400	–	–
	Welcome	Gulf Oil Corporation	0.512	10,000	400	60	–
Maryland	Baltimore	Continental Oil Co.	0.215	500,000	15,000	1,000	–
Massachusetts	Malden	Solvent Chemical Co.	0.008	3,000	–	–	–
Michigan	Midland	Dow Chemical	1.172	70,000	26,000	3,000	900
Mississippi	Pascagoula	First Mississippi Corp.	0.427	20,000	7,000	1,000	30
Missouri	St. Louis	Monsanto	4.641	20,000†	400,000	100,000	50,000
Nevada	Henderson	Montrose Chemical Corp. of California	0.112	10,000	400	–	–

Table B-2 (continued)

State	Location	Company	Total Benzene Emission Rate 10^6Kg/yr	Population Exposed to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	> 10.0
New Jersey	Bound Brook	American Cyanamid	0.266[a]				
	Bound Brook	Union Carbide	0.068	70,000	3,000	300	–
	Elizabeth	Reichhold Chemical	1.353	400,000†	90,000	20,000	8,000
	Fords	Tenneco	1.160	400,000	14,000	2,000	600
	Gibbstown	E. I. du Pont	0.637	200,000	7,000	900	200
	Kearny	Standard Chlorine Chem.	0.060	30,000	600	–	–
	Westville	Texaco	0.029	3,000	–	–	–
New York	Niagara Falls	ICC Industries	N.A.[a]				
	Niagara Falls	Occidental Petroleum	0.024	80,000	2,000	–	–
	Niagara Falls	Solvent Chemical Co.	0.07				
	Syracuse	Allied Chemical Corp.	0.115	100,000	5,000	–	–
Ohio	Haverhill	United States Steel	0.09	3,000	100	–	–
Pennsylvania	Beaver Valley	Arco/Polymers	0.300	20,000	700	70	–
	Bridgeville	Koppers Company	1.450	100,000†	8,000	2,000	600
	Clairton	United States Steel	N.A.				
	Frankford	Allied Chemical Corp.	0.250	800,000	30,000	3,000	–
	Neville Island	United States Steel	1.740	300,000†	270,000	30,000	12,000
	Philadelphia	Gulf Oil Corporation	0.325	1,000,000	40,000	5,000	–
Texas	Baytown	Exxon Corporation	0.330	40,000	5,000	600	–
	Beaumont	E. I. du Pont	0.987[a]	100,000	28,000	4,000	1,000
	Beaumont	Union Oil Co. of Calif.	0.280				
	Big Spring	American Petrofina	0.170	30,000	3,000	40	–
	Borger	Phillips Petroleum	0.330	10,000	1,500	200	–
	Chocolate Bayou	Monsanto	0.524	6,000	300	30	–
	Corpus Christi	Coastal States Gas	0.016[a]				
	Corpus Christi	Sun Oil Company	0.108	100,000	6,000	400	–
	Corpus Christi	Union Pacific Corp.	0.182				
	Freeport	Dow Chemical	1.534	20,000†	10,000	2,000	600
	Houston	Arco/Polymers	0.094[a]				
	Houston	The Charter Company	0.009				
	Houston	Joe Oil	N.A.	1,000,000†	110,000	20,000	5,000
	Houston	The Merichem Company	N.A.				
	Houston	Petro-Tex Chemical	2.224				
	Odessa	El Paso Natural Gas	0.179	70,000	6,000	100	–
	Oyster Creek	Dow Chemical	0.182	1,000	60	–	–
	Phillips	Phillips Petroleum Co.	N.A.				

Table B-2 (concluded)

State	Location	Company	Total Benzene Emission Rate 10^6Kg/yr	Population Exposed to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	> 10.0
Texas (cont'd)	Port Arthur	Arco/Polymers	0.124[a]				
	Port Arthur	Gulf Oil Corp.	0.051	50,000	2,000	20	-
	Port Arthur	Texaco	0.50				
	Seadrift	Union Carbide Corp.	0.300	3,000	800	200	-
	Sweeney	Phillips Petroleum Co.	0.703	9,000	2,000	600	100
	Texas City	Marathon Oil Co.	0.021[a]				
	Texas City	Monsanto	1.784	20,000	28,000	4,000	1,000
	Texas City	Standard Oil (Ind.)	0.846				
Washington	Anacortes	Stimson Lumber Co.	N.A.				
	Kalama	Kalama Chemical	0.025	1,000	-	-	-
West Virginia	Charleston	Union Carbide Corp.	0.149	70,000	2,700	-	-
	Follansbee	Koppers Company	N.A.				
	Moundsville	Allied Chemical	0.436	20,000	2,700	300	-
	Natrium	PPG Industries	0.340	6,000	300	30	-
	New Martinsville	Mobay Chemical	0.427	10,000	2,700	300	-
	Willow Island	American Cyanamide	0.189	3,000	100	-	-
Puerto Rico	Guayama	Phillips Petroleum	0.585	100,000	17,000	4,000	-
	Penuelas	Commonwealth Oil	0.375[a]				
	Penuelas	Union Carbide Corp.	0.162	100,000	5,000	600	80
			TOTALS	6,000,000	1,300,000	200,000	80,000

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a - When more than one chemical manufacturing facility is located in a city, it is assumed that they are in approximately the same area and the emission levels are summed.

*Annual average concentrations; to convert to 8-hour worst case, multiply by 25; to convert to $\mu g/m^3$, multiply by 3.2; a dash (-) signifies that no exposed population was estimated by our method for the average annual concentrations listed. There may be some population exposed to those concentrations for shorter periods of time.

†Some population may be exposed to annual average concentrations above 0.1 ppb beyond 20 km.

‡Totals are rounded to one significant figure.

Source: SRI estimates.

APPENDIX C

POPULATION EXPOSURES FROM COKE-OVEN OPERATIONS BY LOCATION

Table C-1

ESTIMATED POPULATION EXPOSED TO BENZENE FROM COKE OVENS, BY PLANT LOCATION

Location*	Plant Name*	Company*	Annual Coal Capacity* (tons)	Emission Rate† (g/sec)	Population Exposed† to Benzene (ppb)†			
					0.1-1.0	1.1-4.0	4.1-10.0	>10.0
ALABAMA								
Tarrant	Tarrant Plant	Alabama By-Product Co.	1,200,000	1.0	2,000			
Holt	Holt Plant	Empire Coke Co.	150,000	0.13	-			
Woodward	Woodward Plant	Koppers Company, Inc.	800,000	0.69	-			
Gadsden	Gadsden Plant	Republic Steel Corp.	820,000	0.71	480			
Thomas	Thomas Plant	Republic Steel Corp.	185,000	0.16	-			
Birmingham	Birmingham Plant	U.S. Pipe and Foundry Co.	1,175,000	1.0	6,250			
Fairfield	Fairfield Plant	U.S. Steel Corp.	2,500,000	2.2	-			
CALIFORNIA								
Fontana	Fontana Plant	Kaiser Steel Corp.	2,336,000	2.0	1,420			
COLORADO								
Pueblo	Pueblo Plant§	CF&I Steel Corp.	1,332,000	1.1	-			
ILLINOIS								
Granite City	Granite City Steel Div.	National Steel Corp.	1,132,000	0.97	-			
Chicago	Chicago Plant	Interlake, Inc.	949,000	0.82	830			
Chicago	Wisconsin Steel Works	International Harvester Co., Wisconsin Steel Div.	991,000	0.85	-			
South Chicago	South Chicago Plant	Republic Steel Corp.	590,000	0.51	-			
INDIANA								
Chesterton	Burns Harbor Plant	Bethlehem Steel Corp.	2,630,000	2.3	-			
Indianapolis	Prospect Street Plant	Citizens Gas & Coke Utility	675,000	0.58	60			
Terre Haute	Terre Haute Plant	Indiana Gas and Chemical Corp.	204,000	0.18	-			
East Chicago	Plant No. 2	Inland Steel Co.	3,102,000	2.7**	21,330			
East Chicago	Plant No. 3	Inland Steel Co.	1,642,000	1.4				
Gary	Gary Plant	U.S. Steel Corp.	3,700,000	3.2	36,860			
Indiana Harbor	Indiana Harbor Plant	Youngstown Sheet and Tube Co.	2,100,000	1.8	580			
KENTUCKY								
Ashland	Semet	Solvay Div., Allied Chemical Corp.	1,600,000	1.4	550			
MARYLAND								
Sparrows Point	Sparrows Point Plant	Bethlehem Steel Corp.	4,820,000	4.1	19,380			
MICHIGAN								
Detroit	Semet	Solvay Div., Allied Chemical Corp.	900,000	0.77	-			
Dearborn	Steel Plant	Ford Motor Co.	1,800,000	1.5	2,200			
Zug Island (Detroit)	Zug Island Plant	Great Lakes Steel Div., National Steel Corp.	2,850,000	2.5	33,930			

Table C-1 (continued)

Location[*]	Plant Name[*]	Company[*]	Annual Coal Capacity[*] (tons)	Emission Rate[†] (g/sec)	Population Exposed[†] to Benzene (ppb)[‡] 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
MINNESOTA								
St. Paul	St. Paul Plant	Koppers Company, Inc.	250,000	0.22	-			
Duluth	Duluth Plant	U.S. Steel Corp.	850,000	0.73	-			
MISSOURI								
St. Louis	St. Louis Plant	Great Lakes Carbon Corp., Missouri Coke & Chemical Div.	450,000	0.39	-			
NEW YORK								
Buffalo	Harriet Plant	Semet-Solvay Div., Allied Chemical Corp.	400,000	0.34	-			
Lackawana	Lackawana Plant[§]	Bethlehem Steel Corp.	4,250,000	3.7	20,250			
Buffalo	Donner-Hanna Plant	Donner-Hanna Coke Corp.	1,387,000	1.2	3,720			
OHIO								
Ironton	Ironton Plant	Semet-Solvay Div., Allied Chemical Corp.	1,230,000	1.1	2,370			
New Miami	Hamilton Plant	Armco Steel Corp.	934,000	0.80	10			
Middletown	Middletown Plant[§]	Armco Steel Corp.	748,000	0.64	-			
Painesville	Painesville Plant	Diamond Shamrock Corp.	215,000	0.18	-			
Portsmouth	Empire	Detroit Steel Div., of Cyclops Corp.	600,000	0.52	-			
Toledo	Toledo Plant[§]	Interlake Inc.	438,000	0.38	-			
Cleveland	Cleveland Plant	Republic Steel Corp.	2,220,000	1.9	5,760			
Massilon	Massilon Plant	Republic Steel Corp.	250,000	0.22	-			
Warren	Warren Plant	Republic Steel Corp.	650,000	0.56	-			
Youngstown	Youngstown Plant	Republic Steel Corp.	1,500,000	1.3	1,990			
Lorain	Lorain Cuyahoga Works	U.S. Steel Corp.	2,700,000	2.3	2,870			
Campbell	Campbell Plant	Youngstown Sheet and Tube Co.	2,300,000	2.0	4,070			
PENNSYLVANIA								
Swedeland	Alan Wood Plant	Alan Wood Steel Co.	803,000	0.69	-			
Bethlehem	Bethleham Plant[§]	Bethlehem Steel Corp.	2,210,000	1.9	5,550			
Johnstown	Rosedale Div.	Bethlehem Steel Corp.	550,000	0.47[**]	2,680			
Johnstown	Franklin Div.	Bethlehem Steel Corp.	1,680,000	1.4				
Midland	Alloy & Stainless Steel Div.	Crucible Inc., Div. Colt Industries	657,000	0.57	-			
Aliquippa	Aliquippa Plant[§]	Jones and Laughlin Steel Corp.	2,250,633	1.9	-			
Pittsburgh	Pittsburgh Plant	Jones and Laughlin Steel Corp.	2,587,404	2.2	10,170			
Erie	Erie Plant	Koppers Company, Inc.	290,000	0.25	-			
Philadelphia	Philadelphia Plant	Philadelphia Coke Division	715,400	0.61	2,430			
Pittsburgh	Neville Island Plant	Shenango Inc.	1,022,000	0.88	-			
Clairton	Clairton Plant[§]	U.S. Steel Corp.	9,670,000[††]	8.3	102,990			
Fairless Hills	Fairless Hills Plant	U.S. Steel Corp.	1,800,000	1.5	4,130			
Monessen	Wheeling	Pittsburgh Steel Corp.	750,000	0.65	-			

Table C-1 (concluded)

Location*	Plant Name*	Company*	Annual Coal Capacity* (tons)	Emission Rate† (g/sec)	Population Exposed† to Benzene (ppb)‡ 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
TENNESSEE								
Chattanooga	Chattanooga Plant	Chattanooga Coke and Chemicals Co.	204,400	0.18	-			
TEXAS								
Houston	Houston Plant	Armco Steel Corp.	584,000	0.50	-			
Lone Star	E. B. Germany Plant	Lone Star Steel Co.	498,000	0.43	-			
UTAH								
Provo	Geneva Works§	U.S. Steel Corp.	2,000,000	1.7	20			
WEST VIRGINIA								
Weirton	Weirton Mainland Plant	Weirton Steel Div., National Steel Corp.	2,500,000	2.2**	-			
Weirton	Weirton's Brown's Island Plant	Weirton Steel Div., National Steel Corp.	1,825,000	1.6				
Fairmont	Fairmont Plant	Sharon Steel Corp.	300,000	0.26	-			
Follansbee	East Steubenville Plant	Wheeling-Pittsburgh Steel Corp.	2,500,000	2.2	3			
WISCONSIN								
Milwaukee	Milwaukee Solvay Coke Co.	A Division of Picklands Mather and Co.	347,000	0.30	-			
			TOTAL††		300,000			

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[*] Keystone Coal Industries Manual (1975) and Varga (1974), as cited in Suta (1977).

[†] SRI estimates; population estimates are based on detailed census tract information available from Suta (1977).

[‡] Annual average concentrations; to convert to 8-hour worst case, multiply by 25; to convert to $\mu g/m^3$, multiply by 3.2. A dash (-) indicates that no exposed population was estimated by our method for those annual average concentrations listed. There may be some population exposed to those concentrations for shorter periods of time.

[§] Coke oven operations producing benzene as a by-product (PEDCo, 1977).

[**] Coke oven operations located in approximately the same place. Their emission rates are summed.

[††] Total is rounded to one significant figure.

[‡‡] Based on a 1973 emission inventory.

APPENDIX D

POPULATION EXPOSURES
FROM
PETROLEUM REFINERIES BY LOCATION

Table D-1

ESTIMATED POPULATION EXPOSED TO BENZENE FROM PETROLEUM REFINERIES BY PLANT LOCATION

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
ALABAMA							
Holt							
Warrior Asphalt Co. of Alabama, Inc.	.17	2.1	.07	-	-	-	-
Theodore							
Marion Oil Co.	1.04	13.5	.43	-	-	-	-
Tuscaloosa							
Hunt Oil Co.	1.65	21.5	.68	-	-	-	-
Total	2.86	37.1					
ALASKA							
Kenai							
Chevron USA Inc.	1.28	16.6	.53[a]				
Tesoro Petro Corp.	2.21	28.7	.91	-	-	-	-
North Slope							
At-Rich Co.	.75	9.8	.31	-	-	-	-
Total	4.24	55.1					
ARIZONA							
Fredonia							
Arizona Fuels Corp.	.23	3.0	.10	-	-	-	-
Total	.23	3.0					
ARKANSAS							
El Dorado							
Lion Oil Co.	2.69	35.0	1.11	-	-	-	-

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1. Source: Oil and Gas Journal, May 28, 1977.

2. Source: SRI estimates.

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)[*]			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
ARKANSAS (continued)							
Norphlet							
MacMillan Ring-Free Oil Co., Inc.	.26	3.3	.11	–	–	–	–
Smackover							
Cross Oil & Refining Co. of Arkansas	.34	4.4	.14	–	–	–	–
Stephens							
Crystal Oil Co.	.22	2.9	.09	–	–	–	–
Total	3.51	45.6					
CALIFORNIA							
Bakersfield							
Chevron USA Inc.	1.51	19.6	.62[a]				
Kern Co. Refinery Co.	.92	12.0	.38				
Lion Oil Co. (TOSCO)	2.21	28.7	.91				
Mohawk Petroleum Corp., Inc.	1.28	16.7	.53				
Road Oil Sales	.09	1.1	.04				
Sabre Refining Co.	.20	2.6	.08				
Sunland Refining Co.	.81	10.6	.34				
West Coast Oil Co.	.87	11.3	.36	400	–	–	–
Benicia							
Exxon Co.	5.12	66.4	2.11	–	–	–	–
Carson							
Atlantic-Richfield[**]	10.16[§]	312.2	9.91[a]				
Fletcher Oil and Refining Co.	1.11	14.5	.46	70,000	–	–	–

Table D-1 (continued)

Location[1]	Total Capacity ($10^6 m^3$)[1]	Total Emission ($10^6 g$)[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
CALIFORNIA (continued)							
El Segundo							
Chevron USA Inc.**	23.51§	702.5	22.30	60,000†	-	-	-
Hanford							
Beacon Oil Co.	.71	9.3	.29	-	-	-	-
Hercules							
Pacific Refining Co.	3.09	40.2	1.28	-	-	-	-
Long Beach							
Edgington Oil Co. Inc.	1.71	22.3	.71	-	-	-	-
Los Angeles							
Union Oil Co. - Calif.	6.27	81.5	2.59	-	-	-	-
Martinez							
Lion Oil Co. (TOSCO)	7.31	95.1	3.02[a]				
Shell Oil Co.	5.80	75.4	2.40	500	-	-	-
Newhall							
Newhall Refining Co. Inc.	.63	8.2	.26	-	-	-	-
Oildale							
Golden Bear Div., Witco. Chemical Corp.	.61	7.9	.25[a]				
San Joaquin Refining Co.	1.57	20.4	.65	-	-	-	-
Oxnard							
Oxnard Refinery	.15	1.9	.06	-	-	-	-
Paramount							
Douglas Oil Co.	2.70	35.1	1.11	-	-	-	-
Richmond							
Shell Oil Co.**	21.20	550.8	17.49	100,000	-	-	-
San Francisco							
Union Oil Co. - Calif.	6.44	83.8	2.66	-	-	-	-

Table D-1 (continued)

Location[1]	Capacity ($10^6 m^3$)[1]	Emission ($10^6 g$)[2]	Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
CALIFORNIA (continued)							
Santa Fe Springs							
Gulf Oil Co.	2.99	38.9	1.23[a]				
Powerline Oil Co.	2.56	33.3	1.06	-	-	-	-
Santa Maria							
Douglas Oil Co.	.55	7.2	.23	-	-	-	-
Signal Hill							
MacMillan Ring-Free Oil Co.	.67	8.7	.28	-	-	-	-
South Gate							
Lunday-Thagard Oil Co.	.49	6.4	.20	-	-	-	-
Torrance							
Mobile Oil Corp.	7.17	93.2	2.96	400	-	-	-
Ventura							
USA Petrochem Corp.	.87	11.3	.36	-	-	-	-
Wilmington							
Champlin Petroleum Co.	1.78	23.1	.73[a]				
Shell Oil Co.	5.22	67.9	2.16				
Texaco Inc.	4.35	56.6	1.80	200	-	-	-
Total	132.63	2,576.7		231,500			
COLORADO							
Commerce City							
Asamera Oil (U.S.) Inc.	1.31	17.0	.54	-	-	-	-
Denver							
Continental Oil Co.	1.89	24.5	.78	-	-	-	-
Fruita							
Gary Western Co.	.53	6.94	.22	-	-	-	-
Total	3.73	48.44					

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)^1$	Total Emission $(10^6 g)^2$	Emission Rate $(g/sec)^2$	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
DELAWARE							
Delaware City							
Getty Oil Co. Inc.	8.13	105.6	3.35	100	-	-	-
Total	8.13	105.6		100			
FLORIDA							
St Marks							
Seminole Asphalt Refinery Co.	.33	4.3	.14	-	-	-	-
Total	.33	4.3					
GEORGIA							
Douglasville							
Young Refining Co.	.28	3.6	.12	-	-	-	-
Savannah							
Amoco Oil Co.	8.71	11.3	.36	-	-	-	-
Total	8.99	14.9					
HAWAII							
Barbers Point							
Chevron USA Inc.	2.32	30.2	.96	-	-	-	-
Ewa Beach							
Hawaii Independent Refinery Inc.	3.42	44.5	1.41	-	-	-	-
Total	5.74	74.7					

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)[*]			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
ILLINOIS							
Blue Island							
Clark Oil and Refining Co.	3.86	50.1	1.59	-	-	-	-
Colmar							
Yetter Oil Co.	.06	.8	.02	-	-	-	-
Hartford							
Clark Oil and Refining Co.	3.03	39.4	1.25	-	-	-	-
Joliet							
Mobil Oil Corp.	10.45	135.8	4.31	6,000	-	-	-
Lawrenceville							
Texaco Inc.	4.88	63.4	2.01	-	-	-	-
Lemont							
Union Oil Co. of Calif.[**]	8.76[§]	294.8	9.36	7,000	-	-	-
Lockport							
Texaco Inc.	4.18	54.3	1.72	-	-	-	-
Plymouth							
Wireback Oil Co. Inc.	.10	1.4	.04	-	-	-	-
Robinson							
Marathon Oil Co.	11.32	147.1	4.67	400	-	-	-
Wood River							
Amoco Oil Co.[**]	5.51	71.7	2.28[a]				
Shell Oil Co.	16.43[§]	535.8	17.01	100,000[†]	-	-	-
Total	68.58	1,463.18		113,400			

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
INDIANA							
East Chicao							
Energy Coop. Inc.	7.31	95.1	3.02	300	-	-	-
Fort Wayne							
Gladieux Refinery Inc.	.71	9.2	.29	-	-	-	-
Indianapolis							
Rock Island Refining Corp.	2.53	32.9	1.04	-	-	-	-
Laketon							
Laketon Asphalt Refining Inc.	.47	6.1	.19	-	-	-	-
Mt. Vernon							
Indiana Farm Bureau Coop. Association Inc.	.12	1.6	.05	-	-	-	-
Princeton							
Princeton Refinery Inc.	.27	3.5	.11	-	-	-	-
Whiting							
Amoco Oil Co.	21.19	275.4	8.74	4,000	-	-	-
Total	33.31	423.8		4,300			
KANSAS							
Arkansas City							
Apco Oil Co.	2.68	34.9	1.11	-	-	-	-
Augusta							
Mobil Oil Corp.	2.90	37.7	1.20	-	-	-	-
Chanute							
Mid Amer Refinery Co.	.18	2.3	.07	-	-	-	-
Coffeyville							
CRA Inc.	2.81	36.5	1.16	-	-	-	-

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)^1$	Total Emission $(10^6 g)^2$	Emission Rate $(g/sec)^2$	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
KANSAS (continued)							
El Dorado							
Getty Oil Co.**	4.57[§]	151.8	4.82[a]				
Pester Refining Co.	1.31	17.0	.54	80	–	–	–
Kansas City							
Phillips Petroleum Co.	5.22	67.9	2.16	–	–	–	–
McPherson							
Nat. Coop. Refinery Assoc.	3.14	40.9	1.30	–	–	–	–
Phillipsburg							
CRA Inc.	15.32	199.2	6.32	200	–	–	–
Shallow Water							
E-Z Serve	.55	7.2	.23	–	–	–	–
Wichita							
Derby Refining Co.	1.45	18.1	.60	–	–	–	–
Total	40.13	613.5		280			
KENTUCKY							
Betsy Layne							
Ky Oil & Refining Co. Inc.	.03	.04	.01	–	–	–	–
Catlettsburg							
Ashland Petr. Co.**	7.88[§]	361.0	11.46	6,000	–	–	–
Louisville							
Louisville Refining Co.	1.46	19.0	.60	–	–	–	–
Somerset							
Somerset Refinery Inc.	.17	2.3	.07	–	–	–	–
Total	9.54	382.34		6,000			

Table D-1 (continued)

Location[1]	Total Capacity ($10^6 m^3$)[1]	Total Emission ($10^6 g$)[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
LOUISIANA							
Baton Rouge							
Exxon Co.	29.60[§]	628.7	19.96	200,000[†]	–	–	–
Belle Chasse							
Gulf Oil Co., Alliance Refinery**	11.4[§]	353.7	11.23	6,000	–	–	–
Chalmette							
Tenneco Oil Co.**	4.93[§]	167.0	5.3	2,000	–	–	–
Church Point							
Canal Refining Co.	.26	3.4	.11	–	–	–	–
Convent							
Texaco	8.13	105.6	3.35	20	–	–	–
Cotton Valley							
Kerr-McGee Refining Corp.	.64	8.30	.26	–	–	–	–
Garyville							
Marathon Oil Co.	11.61	150.9	4.79	200	–	–	–
Hosston							
Bayou St. Oil Corp.	.23	3.0	.10	–	–	–	–
Jennings							
Evangeline Refining Co. Inc.	.29	3.8	.12	–	–	–	–
Lake Charles							
Cities Service Oil Co.	15.56[§]	303.0	9.62a				
Continental Oil Co.	4.82	62.6	1.99	6,000	–	–	–
Lisbon							
Claiborne Gasoline Co.	.38	4.9	.16	–	–	–	–
Meraux							
Murphy Oil Co.	5.37	69.8	2.22	–	–	–	–

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)^1$	Total Emission $(10^6 g)^2$	Emission Rate $(g/sec)^2$	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
LOUISIANA (continued)							
Metairie							
Good Hope Refineries Inc.	3.86	50.2	1.59	-	-	-	-
Norco							
Shell Oil Co.	13.93	181.1	5.75	400	-	-	-
Port Allen							
Placid Refining Co.	1.99	25.8	.82	-	-	-	-
Princeton							
Calumet Refining Co.	.14	1.8	.06	-	-	-	-
Shreveport							
Atlas Production Co., Div. of Pennzoil**	2.61§	207.3	6.58	30,000	-	-	-
St. James							
LaJet Inc.	.83	10.8	.34	-	-	-	-
Venice							
Gulf Oil Co.	1.67	21.7	.69		-	-	-
Total	118.25	2,363.4		244,620			
MARYLAND							
Baltimore							
Amoco Oil Co.	.87	11.3	.36[a]				
Chevron USA Inc.	.78	10.2	.32	-	-	-	-
Total	1.65	21.5					
MICHIGAN							
Alma							
Total Petroleum Inc.	2.32	30.2	.96	-	-	-	-

Table D-1 (continued)

Location[1]	Total Capacity ($10^6 m^3$)[1]	Total Emission ($10^6 g$)[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
MICHIGAN (continued)							
Bay City							
Dow Chemical USA	1.21§	135.5	4.30	6,000	-	-	-
Carson City							
Crystal Refining Co.	.36	4.7	.15	-	-	-	-
Detroit							
Marathon Oil Co.	3.77	49.0	1.56	-	-	-	-
Kalamazoo							
Lakeside Refining Co.	.33	4.2	.13	-	-	-	-
West Branch							
Osceola Refinery Div., Texas American Petrochemicals Inc.	.72	9.3	.30	-	-	-	-
Total	8.71	212.9		6,000			
MINNESOTA							
Rosemount							
Koch Refining Co.	7.39	96.1	3.05	10	-	-	-
St. Paul Park							
Northwest Refining Co., Div. of Ashland Oil Co.	3.83	49.8	1.58	-	-	-	-
Wrenshall							
Continental Oil Co.	1.36	17.7	.56	-	-	-	-
Total	12.58	163.6		10			
MISSISSIPPI							
Lumberton							
Southland Oil Co.	.33	4.3	.14	-	-	-	-
Pascagoula							
Chevron USA Inc.**	16.3	422.5	13.41	30,000	-	-	-

Table D-1 (continued)

Location[1]	Total Capacity ($10^6 m^3$)[1]	Total Emission ($10^6 g$)[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
MISSISSIPPI (continued)							
Purvis							
Amerada-Hess Corp.	1.65	21.5	.68	-	-	-	-
Sandersville							
Southland Oil Co.	.60	7.85	.25	-	-	-	-
Yazoo City							
Southland Oil Co.	.23	3.0	.10	-	-	-	-
Total	19.11	459.2		30,000			
MISSOURI							
Sugar Creek							
Amoco Oil Co.	6.21	80.7	2.56	-	-	-	-
Total	6.21	80.7					
MONTANA							
Billings							
Continental Oil Co.	3.05	39.6	1.26[a]				
Exxon Co.	2.61	34.0	1.08	-	-	-	-
Cut Bank							
Westco Refining Co.	.27	3.5	.11	-	-	-	-
Great Falls							
Phillips Petroleum Co.	.35	4.5	.14	-	-	-	-
Kevin							
Big West Oil Co.	.30	3.87	.12	-	-	-	-
Laurel							
Cenex	2.35	30.5	.97	-	-	-	-
Wolf Point							
Tesoro Petroleum Corp.	.15	1.9	.06	-	-	-	-
Total	9.08	117.87					

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
NEBRASKA							
Scottsbluff							
CRA Inc.	.29	3.8	.12	-	-	-	-
Total	.29	3.8					
NEW HAMPSHIRE							
Newington							
Atlantic Terminal Corp.	.75	9.8	.31	-	-	-	-
Total	.75	9.8					
NEW JERSEY							
Bayonne							
National Oil Recovery Corp.	.35	4.5	.14	-	-	-	-
Linden							
Exxon Co.	16.54	215.0	6.83	40,000	-	-	-
Paulsboro							
Mobil Oil Corp.	5.69	73.9	2.35	-	-	-	-
Perth Amboy							
Chevron USA Inc.	9.75	126.8	4.02	7,000	-	-	-
Westville							
Texaco, Inc.	5.12§	179.6	5.7	4,000	-	-	-
Total	37.45	599.8		51,000			
NEW MEXICO							
Artesia							
Navajo Refining Co.	1.74	22.6	.72	-	-	-	-
Bloomfield							
Plateau Inc.	.49	6.3	.20[a]				
Thriftway Co.	.44	5.7	.18	-	-	-	-
Ciniza							
Shell Oil Co.	1.04	13.6	.43	-	-	-	-

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
NEW MEXICO (continued)							
Farmington							
Giant Refining Co. Inc.	.51	6.6	.21	–	–	–	–
Kirtland							
Caribou Four Corners Inc.	.17	2.2	.07	–	–	–	–
Lovington							
Southern Union Refining Co.	2.23	29.0	.92	–	–	–	–
Monument							
Southern Union Refining Co.	.30	3.9	.12	–	–	–	–
Total	6.92	96.82					
NEW YORK							
Buffalo							
Mobil Oil Corp.	2.50	32.4	1.03	–	–	–	–
N. Tonawanda							
Ashland Petroleum**	3.71§	187,7	5,96	20,000	–	–	–
Total	6.21	220.1		20,000			
NORTH DAKOTA							
Dickson							
Northland Oil & Refining Co.	.29	3.8	.12	–	–	–	–
Mandan							
Amoco Oil Co.	2.84	37.0	1.17	–	–	–	–
Williston							
Westland Oil Co.	.27	3.5	.11	–	–	–	–
Total	3.40	44.30					

Table D-1 (continued)

Location^1	Total Capacity $(10^6 m^3)^1$	Total Emission $(10^6 g)^2$	Emission Rate $(g/sec)^2$	Population Exposed^2 to Benzene (ppb)*			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
OHIO							
Canton							
Ashland Petroleum Co.	3.71	48.3	1.53	-	-	-	-
Cleves							
Gulf Oil Co.	2.48	32.2	1.02	-	-	-	-
Findlay							
Ashland Petroleum Co.	1.16	15.1	.48	-	-	-	-
Lima							
Standard Oil Co. of Ohio	9.75	126.8	4.02	4,000	-	-	-
Toledo							
Gulf Oil Co.	2.92	38.0	1.20^a				
Standard Oil Co. of Ohio	6.96	90.5	2.87				
Sun Petroleum Prod. Co.	7.26§	222.1	7.05	300,000	-	-	-
Total	34.24	573.0		304,000			
OKLAHOMA							
Ardmore							
Vickers Petroleum Corp.	3.56	46.2	1.47	-	-	-	-
Arnett							
Tonkawa Refining Co.	.35	4.52	.14	-	-	-	-
Cushing							
Hudson Refining Co. Inc.	1.10	14.3	.46	-	-	-	-
Cyril							
Apco Oil Corp.	.81	10.6	.33	-	-	-	-
Duncan							
Sun Petroleum Products Inc.	2.81	36.6	1.16	-	-	-	-
Enid							
Champlin Petroleum Co.	3.12	40.6	1.29	-	-	-	-

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)^1$	Total Emission $(10^6 g)^2$	Emission Rate $(g/sec)^2$	Population Exposed[2] to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
OKLAHOMA (continued)							
Okmulgee							
OKC Refining Co.	1.45	18.9	.60	–	–	–	–
Ponca City							
Continental Oil Co.	7.31	95.1	3.02	100	–	–	–
Stroud							
Allied Materials Corp.	.03	3.6	.11	–	–	–	–
Tulsa							
Sun Petroleum Products Inc.**	5.14§	175.5	5.57	8,000	–	–	–
West Tulsa							
Texaco Inc.	2.90	37.7	1.20	–	–	–	–
Wynnewood							
Kerr-McGee Corp.	2.90	37.7	1.20	–	–	–	–
Total	31.48	521.32		8,100			
OREGON							
Portland							
Chevron USA Inc.	.81	10.6	.34	–	–	–	–
Total	.81	10.6					
PENNSYLVANIA							
Bradford							
Kendall-Amalie Div., Witco Chemical Co.	.52	6.8	.22	–	–	–	–
Emlenton							
Quaker State Oil Refining Corp.	.19	2.5	.98	–	–	–	–
Farmers Valley							
Quaker State Oil Refining Corp.	.38	4.9	.16	–	–	–	–

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)[*]			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
PENNSYLVANIA (continued)							
Freedom							
Valvoline Oil Co. Div. of Ashland Oil Co.	.39	5.1	.16	-	-	-	-
Marcus Hook							
BP Oil Corp.	9.34[§]	138.0	4.38[a]				
Sun Petroleum Products Co.[**]	9.58[§]	304.0	9.65	40,000	-	-	-
Philadelphia							
Atlantic-Richfield Co[**]	10.74	279.2	8.86[a]				
Gulf Oil Co.[**]	11.85[§]	397.8	12.63	2,000,000[†]	-	-	-
Reno							
Pennzoil Co. - Wolf's Head Div.	.12	1.6	.05	-	-	-	-
Roseville							
Pennzoil Co. - Wolf's Head Div.	.58	7.5	.24	-	-	-	-
Warren							
United Refining Co.	3.02	39.2	1.25	-	-	-	-
Total	46.71	1,186.6		2,040,000			
TENNESSEE							
Memphis							
Delta Refining Co.	2.55	2.3	1.05	-	-	-	-
Total	2.55	2.3					
TEXAS							
Abilene							
Pride Refining Co.	2.12	27.5	.87	-	-	-	-

Table D-1 (continued)

Location[1]	Total Capacity ($10^6 m^3$)[1]	Total Emission ($10^6 g$)[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)[*] 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
TEXAS (continued)							
Amarillo							
Texaco Inc.	1.16	15.1	.48		–	–	–
Baytown							
Exxon Co.	22.6	294.3	9.34	40,000	–	–	–
Beaumont							
Mobile Oil Corp.	18.86[§]	550.0	17.46[a]				
Union Oil Co. of Calif.	6.96	181.1	5.75	100,000[†]	–	–	–
Big Spring							
Cosden Oil & Chemical Co.[**]	3.77[§]	285.1	9.05	30,000	–	–	–
Borger							
Phillips Petroleum Co.	5.80	75.5	2.40	–	–	–	–
Carrizo Springs							
Tesoro Petroleum Corp.	1.51	19.7	.63	–	–	–	–
Corpus Christi							
Champlin Petroleum Corp.	7.26[§]	211.7	6.72[a]				
Coastal States Petrochemical Co.	10.7[§]	449.5	14.27				
Howell Corp.[**]	1.23[§]	142.4	4.52				
Quintana Refining Co.[**]	1.36[§]	145.8	4.63				
Saber Refining Co.	.54	7.0	.22				
Southwestern Refining Co. Inc.[**]	6.96[§]	220.8	7.01				
Sun Petroleum Products Co.	3.31[§]	178.6	5.67	200,000[†]	2,000	–	–
Deer Park							
Shell Oil Co.[**]	17.06[§]	648.9	20.6	20,000[†]	–	–	–
El Paso							
Chevron USA Inc.[**]	4.00	105.6	3.35	–	–	–	–
Texaco Inc.	.99	12.8	.41	1,000	–	–	–

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)^1$	Total Emission $(10^6 g)^2$	Emission Rate $(g/sec)^2$	Population Exposed[2] to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
TEXAS (continued)							
Euless							
Texas Asphalt Refining Co.	.35	4.5	.14	-	-	-	-
Ft. Worth							
Winston Refining Co.	1.16	15.1	.48	-	-	-	-
Hearne							
Mid-Tex Refinery	.17	2.3	.07	-	-	-	-
Houston							
Atlantic Richfield Co.**	17.76§	682.2	21.66[a]				
Charter International Oil Co.	3.77§	68.4	2.17				
Crown Central Petroleum Co.**	5.80	150.9	4.79				
Eddy Refining Co.	.18	2.3	.73	1,000,000†	-	-	-
LaBlanca							
Crystal Oil Co.	.28	3.6	.11	-	-	-	-
Longview							
Crystal Oil Co.	.50	6.5	.20	-	-	-	-
Mt. Pleasant							
American Petrofina Inc.	1.51	19.6	.63	-	-	-	-
Nixon							
Pioneer Refining	.15	1.9	.06	-	-	-	-
Odessa							
Shell Oil Co.**	1.86§	51.3	1.63	-	-	-	-
Port Arthur							
American Petrofina Inc.**	6.38§	242.9	7.71[a]				
Gulf Oil Co.**	18.11§	630.6	20.02				
Texaco Inc.	23.56	306.3	9.72	80,000†	600	-	-

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
TEXAS (continued)							
Quitman							
Gulf St. Oil & Refining Co.	.24	3.1	.10	-	-	-	-
San Antonio							
Flint Chemical Co.	.07	0.9	.03[a]				
Howell Corp.	.20	2.6	.08	-	-	-	-
Silsbee							
South Hampton Co.	1.05	13.7	.43	-	-	-	-
Sunray							
Diamond Shamrock Corp.	2.99	38.9	1.23	-	-	-	-
Sweeny							
Phillips Petroleum Co.	6.04	102.4	3,25	10	-	-	-
Texas City							
Amoco Oil Co.**	20.20§	561.0	17.81[a]				
Marathon Oil Co.**	3.83§	102.7	3.26				
Texas City Refining Inc.	4.32	56.2	1.78	60,000†	-	-	-
Three Rivers							
Sigmor Refining Co.	.59	7.7	.24	-	-	-	-
Tucker							
J&W Refining Inc.	.58	7.5	.24	-	-	-	-
Tyler							
LaGloria Oil & Gas Co.	1.70	22.1	.70	-	-	-	-
White Deer							
Dorchester Gas Products Co.	.06	.8	.02	-	-	-	-
Winnie							
Independent Refining Co.**	.77	19.9	.63	-	-	-	-
Young County							
Thriftway Inc.	.06	.8	.02	-	-	-	-
Total	243.22	6,435.6		1,531,010	2,600		

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)^1$	Total Emission $(10^6 g)^2$	Emission Rate $(g/sec)^2$	Population Exposed[2] to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
UTAH							
Asphalt Ridge							
Arizona Fuels Corp.	.06	0.8	.02	-	-	-	-
North Salt Lake							
Husky Oil Co.	1.33	17.4	.55	-	-	-	-
Roosevelt							
Plateau Inc.	.46	6.0	.19	-	-	-	-
Salt Lake City							
Amoco Oil Co.	2.26	29.4	.93[a]				
Chevron USA	2.61	34.0	1.08	-	-	-	-
Woods Cross							
Caribou Four Corners Inc.	.41	5.4	.17[a]				
Morrison Petroleum Co.	.15	1.9	.06				
Phillips Petroleum Co.	1.33	17.4	.55				
Western Refining Co. Inc.	.57	7.4	.23	-	-	-	-
Total	9.18	119.7					
VIRGINIA							
Yorktown							
Amoco Oil Co.	3.08	40.0	1.27	-	-	-	-
Total	3.08	40.0					
WASHINGTON							
Anacortes							
Shell Oil Co.	5.28	68.7	2.18[a]				
Texaco Inc.	4.53	58.9	1.87	40	-	-	-
Ferndale							
Atlantic Richfield Co.	5.57	72.4	2.30[a]				
Mobil Oil Corp.	4.15	53.9	1.71	40	-	-	-

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Emission Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)* 0.1-1.0	1.1-4.0	4.1-10.0	>10.0
WASHINGTON (continued)							
Seattle							
Chevron USA	.26	3.4	.11	–	–	–	–
Tacoma							
Sound Refining Co.	.26	3.40	.11[a]	–	–	–	–
U.S. Oil and Refining Co.	1.24	16.1	.51				
Total	21.29	276.8		80			
WEST VIRGINIA							
Falling Rock							
Pennzoil Co., Elk Refining Div.	.28	3.7	.12	–	–	–	–
Newell							
Quaker State Oil Refining Corp.	.56	7.3	.23	–	–	–	–
St. Marys							
Quaker State Oil Refining Corp.	.28	3.7	.12	–	–	–	–
Total	1.12	14.7					
WISCONSIN							
Superior							
Murphy Oil Corp.	2.64	34.3	1.09	–	–	–	–
Total	2.64	34.3					
WYOMING							
Casper							
Amoco Oil Co.	2.50	32.4	1.03[a]				
Little American Refining Co.	1.42	18.5	.59	–	–	–	–
Texaco Inc.	1.22	15.8	.50				

Table D-1 (continued)

Location[1]	Total Capacity $(10^6 m^3)$[1]	Total Emission $(10^6 g)$[2]	Rate (g/sec)[2]	Population Exposed[2] to Benzene (ppb)[*]			
				0.1-1.0	1.1-4.0	4.1-10.0	>10.0
WYOMING (continued)							
Cheyenne							
Husky Oil Co.	1.37	17.8	.57	-	-	-	-
Cody							
Husky Oil Co.	.63	8.1	.26	-	-	-	-
Cowley							
Sage Creek Refining Co.	.07	.86	.03	-	-	-	-
LaBarge							
Mountaineer Refining Co. Inc.	.02	.23	.007[a]				
Southwestern Refining Co.	.03	.4	.01	-	-	-	-
Lusk							
C&H Refinery Inc.	.01	.14	.005	-	-	-	-
Newcastle							
Tesoro Petroleum Corp.	.61	7.92	.25	-	-	-	-
Osage							
Glacier Park Co.	.24	3.09	.10	-	-	-	-
Sinclair							
Sinclair Oil Corp.	2.84	37.0	1.17	-	-	-	-
Total	10.96	142.24					
	Total Exposed Population†			4,000,000	-	-	-

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a - When more than one refinery is located in a city, it is assumed that they are in approximately the same area and the emission levels are summed.

[*] To convert to $\mu g/m^3$, multiply concentrations by 3.2; to convert to 8-hour worst case, multiply by 25. A dash (-) signifies that no exposed population was estimated by our method for those annual average concentrations listed. There may be some population exposed to those concentrations for shorter periods of time.

[**] Refineries having catalytic reforming of benzene (Oil & Gas Journal, May 28, 1977). Their emission rate is assumed to be twice that of refineries with no benzene production.

Table D-1 (concluded)

[†] Some population may be exposed to annual average concentrations >0.1 ppb beyond 20 km.

[‡] Rounded to one significant figure.

[§] Refineries handling pure benzene (SRI estimates). Emissions from storage and loading of pure benzene were estimated and added to the process emissions from the refinery. If benzene was used captively at the refinery, no loading emissions were assumed. Controlled emissions were assumed for some refineries where information was available (Brothers, personal communication, 1978).

APPENDIX E

PARTIAL LIST OF HYDROCARBONS AND ADDITIVES CONTAINED IN GASOLINE

Table E-1

HYDROCARBONS CONTAINED IN THE VAPOR PHASE OF GASOLINE

Methane
Ethane
Ethylene
Propylene
Propane
Isobutane
Isobutylene; Butene
N-Butane
T-2-Butene
C-2-Butene
3-Me-1-Butene
Isopentane
1-Pentene
2-Me-1-Butene
2-Me-1, 3-Butadiene
N-Pentane
T-2-Pentene
C-2-Pentene
2-Me-2-Butene
2,2-Dimethylbutane
Cyclopentene
3-Me-1-Pentene; 4-Me-1-Pentene
4-Me-C-2-Pentene
2,3-Dimethyl-1-Butene
2-Me-1, 4 Pentadiene
Cyclopentane
4-Me-T-2-Pentene
2,3 Dimethylbutane
2-Me-Pentane
2-Me-1-Pentene
3-Me-Pentane; 1-Hexene; 2-Ethyl-1-Butene
C-3-Hexene
T-3-Hexene
3-Me-Cyclopentene
2-Me-2-Pentene
3-Me-T-2-Pentene
N-Hexane
4,4-Dimethyl-1-Pentene
T-2-Hexene
C-2-Hexene
3-Me-C-2 Pentene

4-4-Dimethyl-T-2-Pentene
Me-Cyclopentane; 3,3-Dimethyl-1-Pentene
2,3-Dimethyl-2-Butene; 2,3,3-Trimethyl-1-Butene
2,4 Dimethylpentane
2,4-Dimethyl-2-Pentene; 3-Ethyl-1-Pentene; 3-Me-1-Hexene
Benzene
2,2,3-Trimethylbutane
2,4-Dimethyl-1-Pentene
4-Dimethyl-C-2-Pentene
1-Me-Cyclopentene
2-Me-C-3-Hexene
2,3-Dimethyl-1-Pentene; 2-Me-3-Hexene
5-Me-1-Hexene; T-3,5-Dimethyl-Cyclopentene; C-3,5-Dimethycyclopentene
3,3-Dimethylpentane
Cyclohexane
4-Me-C-2-Hexene
2-Me-Hexane; 5-Me-C-2-Hexene
1,1-Dimethylcyclopentane
Cyclohexene
2,3-Dimethylpentane
3,4-Dimethyl-C-2-Pentene
3-M3-Hexane
1-C-3-Dimethylcyclopentane; 2-Me-1-Hexene
1-T-3-Dimethylcyclopentane
1-Heptene; 2-Ethyl-1-Pentene
3-Ethyle Pentane; 3-Me-T-2-Hexene
1-T-2-Dimethylcyclopentane
2,2,4-Trimethylpentane
T-3-Heptene
3-Ethylpentane
C-3-Heptene; 1,4-Dimethylcyclopentene
3-Me-C-3-Hexene;
3-Me-T-3-Hexene
3-Ethyl-2-Pentene
T-2-Heptene

Table E-1 (concluded)

N-Heptane; 3-Me-C-2-Hexene
2,3-Dimethyl-2-Pentene
2,3-Dimethylcyclopentene
3--Ethylcyclopentene
C-2-Heptene
1-C-2-Dimethylcyclopentane
2,2-Dimethyl Hexane
Me-Cyclohexane; 1,1,3-Trimethylcyclopentane
2,5-Dimethylhexane
Ethylcyclopentane
2,4-Dimethylhexane
2,2,3-Trimethylpentane
1-T-C-4-Trimethycyclopentane
3,3-Dimethylhexane
Toluene
1-T-2-C-3-Trimethylcyclopentane
Ethylbenzene
P-Xylene
M-Xylene
O-Xylene
C-8 Saturates and Olefins
Isopropylbenzene
N-Propylbenzene
1-Me-3-Ethylbenzene
1-Me-4-Ethylbenzene
1-Me-2-Ethylbenzene
1,3,5-Trimethylbenzene
1,2,4-Trimethylbenzene
1,2,3-Trimethylbenzene
C-9+ Saturates and Olefins
1-Me-2-Isopropylbenzene
1,3-Dimethyl-2-Ethylbenzene; 1,3-Diemthyl-4-Ethylbenzene
C-10 Saturates and Olefins
C-10 + Aromatics

Source: Walker et al, 1975, Table IVB.

Table E-2

COMMON ADDITIVES CONTAINED IN GASOLINE

DETERGENTS AND ANTI-ICING ADDITIVES

Multipurpose Carburetor Detergents

- Polyoxypropylene Ester and Tallow Trimethylenediamine Naphthenate
- Alkyl Aryl Phosphate Esters and N-Oleyl-1,3-Propylenediamine Salts
- Amine-Phosphoric Acid Salt and Olefin Hydrocarbon
- Phosphate Ester Amine Salts
- Nitrogen and Phosphorus-Containing Compositions
- Dimer Acid and N-(10-Phenylstearyl)-1,3-Propylenediamine
- Succinimides and Long Chain Primary Amines
- Derivatives of Polymeric Succinimides
- Polyamine-Alkaryl Carboxylic Acid Reaction Products
- Nitroketonized Amides
- Paraffinic Oil Oxidate-Fatty Amide Salts
- High Molecular Weight Mannich Bases
- Organylimidazolinyl Carbamates
- 2,6-Disubstituted-9-Oxabicyclononanes

Carburetor Detergents

- Carbamates
- Monosubstituted Ureas
- Long Chain Alkylamino Alkyl-Substituted Ureas
- Polyamine, Phenol, Formaldehyde and Acid Reaction Product
- Diamine-Ethoxylated Polyphosphoric Acid Reaction Products
- Guanidine Petroleum Sulfonate
- Polybutene-Substituted Nitrilotrisethylamine
- Substituted Succinamic Acids and Polyolefins
- Polyisobutylene-Substituted Polyamines
- Di(Hydrocarbon)Substituted Alkylene Polyamines
- Trimer Acid Polyesters
- Nonionic Surfactant as Demulsifier

Anti-Icing Additives

- Hexylene Glycol
- Polyhydroxy Alcohol and Fatty Amides
- Polyhydroxy Alcohols and N-(Phenylstearyl)-1,3-Propylenediamine
- Fatty Imidazolines, Amides and Organic Silicon Compounds
- Benzoic Acid with Common Deicers
- Polyethoxylated Propylenediamines

Table E-2 (continued)

PBSA-Based Detergents

- Mixtures with Amine Salts of Sulfonic Acids and Polyethers
- Mixtures with Glycols and Glycol Ethers
- Adipic Acid-N-(Hydroxyethyl)-Ethylene Diamine Reaction Products
- Polyhydric Alcohol Reaction Products
- Polyamine-Polyhydric Alcohols Reaction Products
- Sulfinyl-Containing Hydroxyl Compound Reaction Products

Other Ashless Detergents

- Sulfonyl-Substituted Terpolymers
- Alkane Nitroamines
- Alkane Hydroxyamines
- Oil-Soluble Azo Compounds
- Cyclohexanone Phenylhydrazone Oxidative Treatment

Ash-Forming Detergents

- Overbased Sulfonate and Polyamine-Carboxylic Acids
- Polybutene Succinic Anhydride Treated Overbased Complexes
- Succinic Ester-Metal Salts
- Basic Magnesium Salts of Oil-Soluble Acids
- Coordinated Complexes of Nitrogenous Compounds
- Glycerol Ester

FLOW IMPROVERS AND POUR DEPRESSANTS

Ethylene-Based Polymers

- Vinyl Ester Copolymers
- Vinyl Acetate Copolymer and Fatty Acrylate Homopolymer
- Vinyl Ester Copolymer and Ethylene-Alpha-Olefin Copolymer
- Alkyl Fumarate Copolymers
- Alpha-Monoolefin Copolymers
- Ethylene-Propylene-1,4-Hexadiene Terpolymers
- Oxidized Ethylene-Propylene-Dicyclopentadiene Terpolymers
- Aryl-Substituted Polyolefins

Other Polymeric Additives

- Hydrogenated Styrene-Butadiene Terminated with Polar Groups
- Polybutadienes
- Esters of Styrene-Maleic Anhydride Copolymers
- Alkyl Itaconate-Maleic Anhydride Copolymers
- Vinyl Acetate-Alkyl Fumarate Copolymers
- Mixed Thiolacrylic Esters-Aminomethacrylate Terpolymers
- n-Paraffin-Free Saturated Hydrocarbons

Table E-2 (continued)

Other Additives

- Polysaccharides
- N,N-Dialkylricinoleamides
- Fatty Amides and Salts
- Carboxylic Acid Esters of Polyhydric Alcohols
- Fatty Esters of Alpha-Methylglucoside
- Olefin-Alkyl Halide Reaction Products

OXIDATION, CORROSION AND WEAR INHIBITORS

Oxidation Inhibitors

- Aminoguanidine Derivatives
- Isoindoline Compounds
- 1-Azabicycloalkanes
- Three Component Amine and Amide Mixtures
- Tetracyanoethylene
- N-Substituted Alkoxyalkylamines
- Epichlorohydrin-Alkylamine Reaction Products
- Esters of (3,5-Dihydrocarbyl-4-Hydroxybenzyl)Thiodicarboxylic Acids
- Alkylhydroxyphenyl Thiolacyl Alkanoic Acid Esters
- Diphenyl Bis(3,5-Di-tert-Butyl-4-Hydroxyphenoxy)Silane
- Alkoxy-2,6-Di-tert-Butyl-p-Cresol and Dibutyltin Sulfide
- Alkylamine Salts of Phosphoric Acid Esters
- Bix(Hindered Phenol) Alkylene Diphosphonates
- Esters of Phosphorodithioates
- Phosphorodithioate Ester-Aldehyde Reaction Products
- Dihydrocarbylhydroxyphenyl Phosphonothionates and Phosphates
- Metal Alkyl Ester Tetrapropenylsuccinates

Thermal Stabilizers

- Ethylene-Propylene-Diene Terpolymer--Maleic Acid Reaction Product
- Mannich Base, Dimer Acid and Metal Deactivator
- Substituted Carbamates and Aldehyde-Amine Condensation Products
- Cyclic Borates

Corrosion and Rust Inhibitors

- Bis(1,3-Alkylamino)-2-Propanol and Phosphorylated Derivatives
- Nitro-Nitrito Alkanes, Alkylene Polyamines and Sulfur Reaction Products
- Fatty Amides and Amines
- Tertiary Amine Oxide Concentrates
- 2-Hydroxy-5-Cetylbenzene-1,3-Dicarboxylic Acid
- Mixture of Carboxylic Acids and Phenol-Aldehyde Resins
- Alkyl Sulfoxides
- Mercapto-Substituted Thiadiazoles

Table E-2 (continued)

Antiwear Agents

- Diethers of Diethylene Glycol
- Bis(Hydroxyethyl)Alkane Phosphonates
- Lecithin and Substituted Imidazolines
- Trialkyl Phosphite-Alkenyl Succinic Anhydride Reaction Products
- Phosphorus Pentasulfide-Glycol Reaction Products
- Tetraoctyl Dimethylaminomethylene Diphosphonate
- Substituted Succinic Anhydride and Metal Sequestering Agent
- Tall Oil Fatty Acid

SMOKE AND EMISSION CONTROL AND COMBUSTION AIDS

Smoke Control

- Metal 2-Ethylhexanoates
- Barium Salts of Dialkyl Orthophosphoric Acids
- Barium Carbonate and Dimethyl Ether of Ethylene Glycol
- Barium Sulfonatocarbonate
- Barium Sulfide Treated with Acetic Acid
- Barium-Containing Dispersion
- Colloidal Dispersions
- Barium Alkaryl Sulfonates and Glycol-Ether Solvents
- Overbased Calcium Sulfonates and Nitropropane
- Cyclopentadienyl Manganese Tricarbonyl and Sulfinyl Amines

Emission Control and Combustion Aids

- 4,4'-Benzylidenebis(2,6-Di-tert-Butylphenol)
- Polyalkoxylated Alkylphenol
- Additive Blend
- Boron Trifluoride Etherate-Amine Reaction Products
- Vanadium Salts of Phosphorus Compounds to Improve Rumble
- Tertiary Amines to Aid Air-Fuel Distribution
- Hydrocarbon Wax to Aid Air-Fuel Distribution
- Potassium Hexafluorozirconate and Organic Diamines
- Clay, Phosphate and Boron Oxides for Boiler Fuels

Other Processes

- Molybdenum Naphthenate and Organomanganese Compounds
- Activated Manganese Oxide
- Surface Ignition Suppressors
- Aerosol Starting Agents for Diesels

Table E-2 (continued)

ANTIKNOCK COMPOUNDS

Tetraethyllead

- Triethylaluminum Reactions in Hexamethylphosphoramide
- Tetrahydrofuran Solvent and Catalyst
- Methyl Aluminum Sesquichloride and Sodium Fluoride Catalyst
- Coproduction of Alkali Metal Aluminum Tetraalkyls
- Ethylene dichloride
- Ethylene dibromide

Tetramethyllead

- Sodium Amide Catalyst
- Diglyme, Methanol and Anthracene Catalyst Mixture
- Magnesium-Aluminum Alloy Catalyst
- Lithium-Aluminum and Mercury-Aluminum Catalyst
- Stable Concentrate

Other Lead Compounds

- Hexaorganodiplumbanes
- Triorganolead Compounds
- Spirocyclic Lead Compounds
- Tetraneopentyllead
- Organolead-Silicon Compounds
- Hexaaryldiliead Compounds
- Trialkylplumbylmagnesium Compounds and Organic Halides
- Metallic Lead Reactions Using Metallic Lithium

Nonmetallic Additives

- 1,3-Diimino-2-Hydroxypropanes
- Mixed Nitrosoalkanes and Nitroso Aromatic Dimers
- Aminofulvenes

ANTISTATS, BIOCIDES, DYES AND EMULSIFIED FUELS

Antistatic Agents

- Phosphate Salts of Polyamides and Metal Naphthenates
- Monoamine-Fluorinated Polystyrene Reaction Products
- Cetyl Vinyl Ether-N-Vinylpyrrolidone Copolymers
- Olefin-Maleic Anhydride and Alkyl Vinyl Ether-Maleic Anhydride Copolymers
- Methyl Vinvyl Ether-Maleic Anhydride Copolymers

Biocides

- Cyclic Imines
- N-Alkyl-1,3-Propanediamine
- Naphthenyl Imidazolines

Table E-2 (concluded)

Dyes

- Blue Dye Mixtures
- Azo Dye Compositions

Emulsified Fuels

- Metallized Emulsion
- Carbon Fuel
- Emulsion Formulations

Source: Ramsey, 1974, p. vii-x.